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Environmental Effects of In situ Gasification of Texas Lignite

Texas Univ. at Austin

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A general survey of the environmental effects of the in-situ gasification of Texas lignite was undertaken. The survey emphasized the following subjects:

1. Identification of location, quality and quantity of resources.
2. Assessment of applicable in-situ gasification technologies.
3. Determination of possible adverse air, water and land environmental impacts resulting from gasification.
4. Evaluation of dispersion and mathematical models to predict pollutant transport.
5. Assessment of control technology for water pollutants.

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ENVIRONMENTAL EFFECTS OF IN SITU GASIFICATION OF TEXAS LIGNITE

by

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PREFACE

There is presently a great deal of interest in utilizing Texas lignite since this coal is located near to major energy demand centers in Texas. In 1974, W. R. Kaiser of the Bureau of Economic Geology of the University of Texas reviewed the lignite situation in Texas and obtained a resource estimate of 10 billion tons at strip mining depth (0 to 200 feet overburden), while the deep basin lignite (200 to 5000 feet deep) was estimated to be on the order of 100 billion tons. As a point of reference, the energy content in the former figure is equivalent to the energy content of the proven reserves of oil and gas in Texas. This illustrates that the use of Texas lignite does offer an intermediate-term solution to energy shortfalls in the southwest.

It appears that the major use of the strippable lignite will be in steam power plants, where the strip mine will be located adjacent to the power plant. However, the deep basin lignite cannot be economically recovered by strip or shaft mining at this time. For this lignite there is great interest presently in use of in situ or underground coal gasification (UCG). This is a technology which combines extraction and chemical conversion into a single step. In UCG, a mixture of oxygen, nitrogen, steam, and other gases react with the coal in place to produce a combustible low or medium Btu gas.

The UCG technology has special interest in Texas because of the industry in the Gulf Coast region has used large amounts of natural gas. The nominal distance between lignite supplies and the Gulf Coast is 100 miles, which would allow transport of the gas to the existing industries as well as use at the mine-mouth for production of chemicals or electricity generation.

Illustrative of the state-wide interest in this technology, there are presently two industrially-sponsored field programs in operation. In addition, there are a number of other field programs in the U.S. The success of recent field tests as well as the extensive field programs in the USSR, illustrate that UCG is technically feasible in the U.S. It also appears economically more attractive than comparable technology for producing low, medium, and high Btu gas using first generation surface gasifiers (preceded by conventional mining).

One of the major obstacles to commercialization of underground coal gasification in the U.S. is the lack of knowledge of the environmental impact of this technology. Thus a general survey of available environmental data has been undertaken. In this report, adverse impacts are estimated and important data gaps are identified. Dispersion of water pollutants, subsequent treatment, and site restoration are also discussed.

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ABSTRACT

A general survey of environmental effects of in situ gasification of Texas lignite has been undertaken. The survey has emphasized the following subjects:

(1) Identification of the location, quality, and quantity of lignites in Texas: An exploration model for the various lignite-bearing formations has now been developed, thus allowing evaluation of the commercial potential of various regions of Texas where deep basin lignite can be found. In addition, hydrological and baseline environmental data have been obtained for several areas in Texas.

(2) Assessment of in situ gasification technologies: The effects of various geological conditions, coal characteristics, and operating conditions have been reviewed with reference to Texas lignite. Recent field test data for both air and oxygen injection have been analyzed; it appears that medium Btu gas (oxygen-blown system) will be the most attractive product from in situ gasification.

(3) Determination of possible adverse environmental impacts (air, land, and water) resulting from underground coal gasification (UCG): Air pollution for UCG is essentially the same as for surface gasification, and overall air emissions are lower compared to those from a conventional solid coal burning facility. Subsidence is the major land impact, but it is difficult to predict the extent of subsidence at a given site. The major impact to be considered from UCG is subsurface water pollution; field test data from Texas and Wyoming have been reviewed, both for organic and inorganic compounds. Applicable regulations are discussed.

(4) Evaluation of the dispersion of pollutant species and the application of mathematical models to predict pollutant transport: The literature on dispersion modeling has been reviewed and specific problems posed by typical groundwater flows in Texas are discussed. Hydrological data at UCG test sites in Texas are reviewed.

(5) Assessment of existing water pollution control technology to counteract pollution caused by UCG: The philosophy of site restoration, given that some natural renovation occurs underground after a test is performed, is discussed, and strategies for site restoration have been identified.

Conclusions and recommendations for future research and development dealing with environmental issues are presented in the final section of the report.

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SECTION 1

INTRODUCTION

The future use of underground coal gasification (UCG) in the State of Texas to produce a synthetic fuel to replace oil and gas appears to be both technically and economically feasible. UCG has some environmental advantages over conventional extraction and conversion technologies, in that strip mining is avoided and sulfur emissions are more readily controlled compared to conventional combustion. However, one disadvantage of UCG is that subsurface water pollution does occur, although the short and long term water quality impacts are difficult to predict.

The evaluation of UCG for Texas has required analysis of engineering and geological data available in the literature. Operating data from UCG tests, both in the U.S. and U.S.S.R., and geological, hydrological, and environmental quality data have been accumulated. Relevant data have been analyzed in order to assess the environmental (land, air, water) impact of UCG in Texas. Due to an inadequate data base in the above three areas, engineering analysis must be employed to reach quantitative and in some cases qualitative conclusions. Therefore this report should be considered as a preliminary evaluation of UCG in Texas and serves to identify those areas of research which should be pursued in more detail.

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SECTION 2

CONCLUSIONS

The major alternatives for use of underground coal gasification (UCG) include on-site power production using low Btu gas and manufacture of chemical products from medium Btu gas. Oxygen injection and subsequent processing of the medium Btu gas to produce methanol or gasoline is a promising near-term technological alternative for UCG in Texas.

A detailed analysis of well logs in the State of Texas has led to the development of a regional exploration model for lignite. This model has allowed the estimation of deep basin lignite resources which might be recoverable via underground gasification. The minimum seam thickness for economic or technical feasibility has been selected as five feet; approximately 35 billion short tons of lignite lie in five distinct regions under less than 2000 feet of cover. These blocks have also been evaluated in terms of their hydrology and baseline water quality, although the data are limited. Overall geological criteria for selecting gasifier sites have been developed. Preferred hydrological factors have also been identified.

The technical factors which are conducive to application of UCG for Texas lignites have been identified, including coal properties, seam thickness, water influx, and roof collapse. Water influx appears to be a crucial factor in Texas both in linking and gasification and is expected to be more of a problem in the Wilcox Group than the Jackson Group. Field test data from Texas sites, all in the Wilcox Group, have shown very high water influxes; mathematical model calculations for gas composition indicate that the thermal efficiency of the process suffers greatly for large water influx rates. The role of production pressure in UCG to reduce water influx is also poorly understood. A priori estimates of water influx for a given site are desirable but are difficult to calculate.

As the coal is removed during in situ gasification, a cavity is formed which grows with time. Due to thermal and rock mechanical forces, the roof may collapse continuously while the cavity grows, or it may collapse as a discrete failure of the overlying rock. Roof collapse creates a number of potential operating problems, including loss of gas through fractures to other parts of the formation and increased moisture influx. The moisture entering the cavity may be bound in the collapsed roof rock or flow through the fractured overburden from overlying sands. Potential environmental impacts from roof collapse include increased groundwater contamination due to increased flow in and out of the cavity and disturbance of normal flow patterns, loss of gases into overlying aquifers (impacting water quality), and surface disruptions due to propagation of the roof failure.

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Significant subsidence has occurred at one field test in the United States.

Available data on inorganic and organic water pollutants for UCG field tests in Texas and Wyoming have been accumulated and analyzed. The organic compounds include light hydrocarbons, phenols, oils, and tars. Heavier organics include some polynuclear aromatic hydrocarbons (PAH's) and heterocyclic compounds. Other gaseous components that condense or are absorbed in surrounding groundwater are ammonia, carbon dioxide, hydrogen sulfide, and methane. Qualitatively similar pollutant profiles are obtained.

After gasification is completed, an ash residue remains in the burn cavity which yields soluble inorganic components to reinvading groundwaters. The soluble ash components can greatly increase the total dissolved solids content of the groundwater. These soluble materials include a wide array of ionic species, mainly calcium, sodium, sulfate, and bicarbonate. These components yield increases in non-specific parameters such as conductivity and total dissolved solids. The exact quantities of these materials are a function of initial coal composition, combustion temperature, water temperature, and groundwater composition. There are, however, many other inorganic materials leached into the groundwater which are of interest even though they are present in lesser quantities. These include aluminum, arsenic, barium, boron, iron, zinc, cyanide, selenium, and hydroxide. Again the exact composition depends on the variables cited above.

Field data have indicated that the pollutants tend to decrease both with time and distance from the burn cavities. There are natural means by which the groundwater concentrations can be reduced. Most interpretations of field data attribute the improved water quality to adsorption and ion exchange properties of surrounding strata, precipitation reactions, dilution and dispersion by groundwater flow, and biological conversion reactions. It should be noted that only the last process, biological conversion, is ultimately useful in the final destruction or conversion of harmful contaminants to nonharmful products. Inorganic pollutants are not as susceptible to attenuation as are the organic pollutants.

The conceptual model of pollutant generation and transport proposed in the literature appears valid. Materials having little affinity for solid surfaces, such as many of the TDS components, will not be retained by surrounding strata and will travel at the rate of groundwater flow with little diminution of peak concentrations. Those materials with medium to large affinity for solid surfaces will travel much more slowly and have significant decreases in peak concentrations as time progresses.

Of particular concern is the deposition of tars and oils in the surrounding strata. Some of the materials comprising the tars and oils are toxic chemicals. It appears that the solubility of these components are very low and they have high adsorption affinity for surrounding solid strata. Thus, aqueous concentrations of these components should be low in the region of the tar deposits, and their high affinity for solid surfaces should prevent rapid migration in the water phase. However, considering solubility and adsorption only, it should take a very long time before the source of pollution is dispersed, but little quantitative information is available.

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Dispersion of potential groundwater pollutants has been analyzed and found not to be very significant, due to low groundwater velocities (typically one meter/year or less). Disturbance of aquifer flow patterns and local hydrology may, however, result from roof collapse after gasification is completed. An important consideration in dispersion analysis is the ability of the subsurface strata to adsorb potential contaminants, thus gradually improving water quality after gasification.

The general mathematical models used for prediction and simulation of flow and transport are deemed to be adequate. The science and art of numerical modeling is highly developed, and there are few physical problems which defy analysis. The limitation of numerical models lies in the difficulty in finding the appropriate parameter values to use in the models. Fractures within the porous media present a number of problems for modeling. There is no generally accepted model of the hydraulics of flow in fractured media. Also, development of fractures in the overburden presents an avenue for increased cross-formation flow between neighboring water bearing units.

Monitoring of water quality during and after field tests has shown that water quality can return close to baseline levels as early as one year after the test is completed. Because of limited data at this time, it is not possible to explain completely the improvement in water quality with time or to predict the long term fate of pollutants released to groundwater. Clearly, the mechanisms are complex with many potential physical, chemical, and biological processes that could be important. With the exception of some study of the adsorptive properties of organic compounds on surrounding strata, the important mechanisms affecting long term fate of pollutants are not known. There has been no long term field test from which to obtain real time environmental data, and none of the U.S. tests have been on a commercial scale.

Although local contamination of groundwater can occur, in some cases restoration may not be necessary. It can be argued that regulations on restoration should flexible (decided on an individual case basis) rather than universally requiring all groundwater to be restored. The following questions should be addressed for a given site:

(1) Is the water quality of an aquifer high?
(2) Is the aquifer productive?
(3) Is the aquifer now or potentially a usable source of water?

An aquifer might be declared exempt from restoration (or minimal restoration efforts would be required) if it failed one or more of the above conditions. Restoration bases that have been used in the past in Texas are:

(1) Restoration shall be equal to or better than drinking water standards.
(2) Restoration shall be to baseline water quality or better.

Techniques that could be used for subsurface restoration include:

(1) Treatment of pumped water plus reinjection to the aquifer.
(2) Reliance on natural restoration processes to

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cleanse the in situ water.

(3) Enhancement of the in situ natural restoration processes.

It should be pointed out that techniques (2) and (3) are not based on established knowledge or practice and require development. In addition, the efficiency of method (1) is not known at this time either, although it is commonly used to restore in situ uranium leaching sites.

The treatment and/or disposal of the contaminated water from UCG has not been studied as yet, although treatment of similar types of waters from in-situ shale oil retorting and above ground coal gasification processes has been researched. However, no full-scale treatment scheme exists, and wastewaters specific to in situ coal gasification have not been analyzed in treatability studies.

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SECTION 3

RECOMMENDATIONS

A number of recommendations for further research which have resulted from this project are reported in Section 10. Most of these recommendations arise from the inadequate environmental data base, which must exist for quantitative analysis and prediction of the environmental impact of underground coal gasification in Texas or anywhere else. Some of the more pressing needs include:

(1) Regional hydrochemical mapping and head mapping in lignite-bearing geologic units.
(2) Better laboratory and field data on the influence of operating strategies on mitigating environmental impact. The effects of coal composition, water influx rate, roof collapse, combustion temperature, and groundwater composition on the pollutant release are largely unknown, and biological phenomena occurring underground have received little study. A better understanding of how oxygen vs. air injection affects organic pollutant production and the relationship between sweep efficiency and subsidence are other topics for further research.
(3) Prediction of long term vs. short term water quality impacts. Implicit in this research need is the question of natural renovation as well as dispersion of pollutants underground. Very little data are available at present.
(4) Treatability studies on wastewater produced from UCG, including chemical, physical, and biological effects. Control strategies for site restoration need to be field tested.
(5) Establishment of flexible regulations or criteria for site restoration, due to the large potential variablity in water quality and natural renovation from site to site.

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SECTION 4

THE POTENTIAL OF UNDERGROUND GASIFICATION FOR TEXAS LIGNITE

INTRODUCTION

The Eocene deposits of lignite in Texas form a major energy resource, with roughly 10 billion short tons occurring at depths of less than 200 feet (61 m). More impressively, the deep-basin lignites, those lying between depths of 200 to 5000 feet (61 - 1525 m) beneath the surface, have been estimated to be in excess of 100 billion short tons [1]. This is the energy equivalent of ten times Texas' proven reserves of oil and gas. Obviously all of this lignite cannot be recovered, but the order of magnitude is still significant. While surface mining remains the most economical method of recovering the shallower deposits, in situ techniques, especially in situ or underground gasification, should be considered as serious competitors of shaft mining in the exploitation of the deeper lignites.

Due to the proximity of these lignite deposits to major energy demand centers, especially the concentration of industrial plants along the Texas Gulf Coast, there is a great deal of interest in the exploitation of the resource. It appears that the major use of the strippable lignite will be in steam power plants, where the strip mine will be located adjacent to the power plants. There is great activity planned for the mining of lignite by 1985 (eleven major mines), at which time Texas is projected to become the seventh largest coal mining state. However, the deep basin lignite probably will not be economically recoverable by strip or shaft mining (except in special circumstances where pit mining of multiple seams down to 300 feet (90 m) can be performed). For this lignite there is great interest presently in a technology which combines extraction and chemical conversion into a single step. In UCG, a mixture of oxygen, nitrogen, steam, and other gases is injected into a coal seam and reacts with the coal to produce a combustible gas; the heating value can range from 60 Btu/SCF (2.2 MJ/m^3) to 350 Btu/SCF (13.0 MJ/m^3), depending upon the operating conditions of the seam and the injection gases used [2].

The UCG technology has special interest in Texas because the industry in the Gulf Coast region uses large amounts of natural gas [3]. As discussed in Section 5, the lignite deposits are centrally located with respect to the major energy demand centers in Texas. The nominal distance between energy source and demand point is 100 miles (160 Km), which would allow three possible applications for the gas produced:

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(1) Use of a low Btu gas in a mine-mouth power plant to produce electricity.
(2) Transport of medium Btu gas to demand point for steam raising and process heat in Gulf Coast manufacturing facilities.
(3) On-site or off-site use of medium Btu gas as a chemical feedstock (e.g., in the manufacture of methanol).

The medium Btu gas described above would consist chiefly of carbon monoxide and hydrogen and would require use of pure oxygen (no nitrogen) for in situ gasification. Low Btu gas can be produced by gasification with air. Figure 1 shows the location of the top twenty natural gas consuming counties in 1975. It should be noted that a great deal of natural gas was used then to fuel power plants. The Power Plant and Industrial Fuel Use Act of 1978 has essentially mandated that other fuels replace natural gas as a boiler fuel by 1990.

Illustrative of the state-wide interest in underground coal gasification, there have been two industrially-sponsored field programs operated:
(1) Basic Resources, Inc. (subsidiary of Texas Utilities), near Tennessee Colony (Anderson County).
(2) Texas A & M plus a consortium of ten companies near Alcoa, Texas (Milam County).

Both tests have gasified lignite in the Wilcox Group. The Texas Utilities test has attracted special attention because it is based on a license of the Russian UCG technology (developed between 1930 and the present). Therefore, this test has proprietary restrictions, although a great deal of useful information about the Russian technology is in the open literature [4].

There are currently a number of other field programs in the U.S. [2], [5], most of which are sponsored by the Department of Energy. These include successful field tests by the Laramie Energy Research Center, Lawrence Livermore Laboratory, Morgantown Energy Research Center, and Gulf Oil Company. Private sector tests outside of Texas include those operated by ARCO and the Alberta Research Council. The Livermore tests have emphasized oxygen/steam while the other projects have used air injection.

The recent operating experience in the U. S. as well as the extensive field programs in the USSR, many of which were operated continuously at a gas production rate equivalent to 10 to 30 MWe, illustrate that UCG is technically feasible in the U. S. It also appears economically more attractive than comparable technology for producing low, medium, and high Btu gas using first generation surface gasifiers (preceded by conventional mining)[6]. Two UCG field tests in the U. S. (Hanna and Hoe Creek Sites) have gasified more coal continuously than any gasifier using second generation technology, thus UCG does have considerable promise.

UNDERGROUND COAL GASIFICATION TECHNOLOGY

In situ gasification using air or oxygen injection is based on two steps: pregasification and gasification. The pregasification step is probably the most critical one, since proper seam preparation is necessary for successful gas production. The main step in the preparation of the coal

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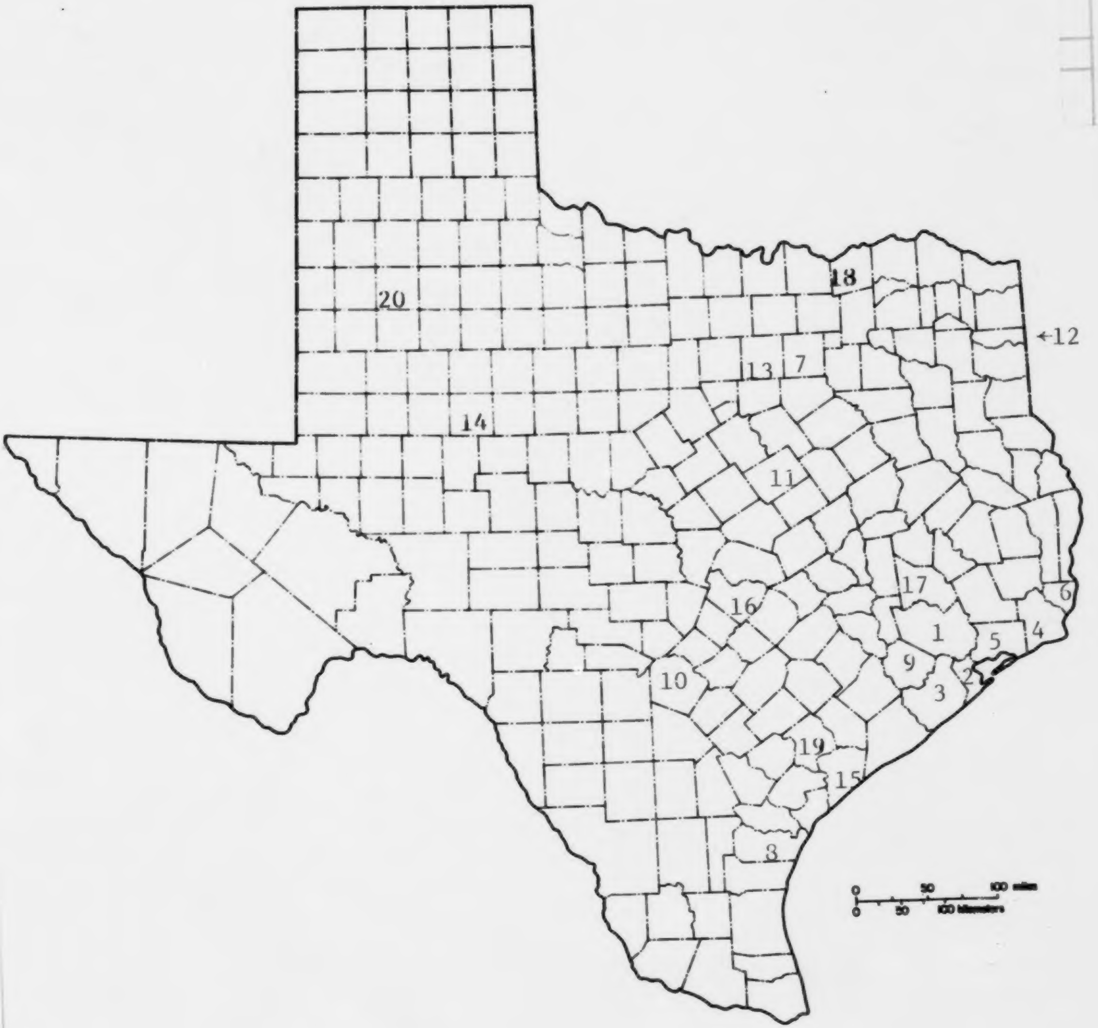
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Figure 1. Location of Top Twenty Counties in Natural Gas Consumption (Texas Railroad Commission, 1975)

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seam is the "linking" of two wells drilled into the coal deposit. In the approach pioneered in the Soviet Union [2], the permeability of the path through the coal is increased by burning part of the coal with air, using an approach called reverse combustion or backward burning. Reverse combustion involves the injection of the oxidant blast in a direction countercurrent to the movement of the combustion front; this method is in contrast to that of forward burning, where the gases and combustion front move cocurrently. Linking between boreholes is achieved after reverse combustion.

The effect of volatiles from the coal and allowable operating pressures are two of the important reasons why backward burning is utilized for permeability enhancement prior to application of forward combustion. In forward burning, volatiles are produced ahead of the combustion front; these volatiles are cooled with the product gases and begin to condense at about 150°C. Plugging of the porous media can occur, requiring high pressure operation. However, in backward burning the volatiles must pass through the flame front, cracking many of the heavier components, which minimizes the potential for plugging. The resulting flow path between injection and production holes permits subsequent use of forward burning, where injection of oxidant at high flow rates can be achieved at low pressures.

In UCG it is important to minimize the loss of both the injected blast and the product gas, which can leak through fractures to surrounding formations as the roof collapses due to removal of the coal. By operating the system at the lowest possible pressure, gas leakage can be minimized. Low pressure operation can only be facilitated through permeability enhancement of the coal seam, which usually entails backward burning, although there are other methods which have been field tested (such as directional drilling) [2].

One other crucial element in the Soviet design for UCG is to form the linkage at the bottom of the seam. The flame front undercuts the coal at the bottom of the seam, and the overlying coal falls into the void. This occurrence promotes efficient gas-solid contact and thus has desirable reaction properties. Another reason for establishing the reaction at the bottom of the seam is to prevent the flame front from moving to the top of the seam (override). Once a channel forms across the top of the seam, the slagged coal ash tends to seal the bottom of the channel, preventing further combustion of coal. This can result in very poor resource utilization and poor quality gas.

The Soviets used a linear well pattern, where two rows of wells are simultaneously linked prior to the gasification process. They also sequenced the introduction of additional rows of wells so that a consistent heating value was produced [2]. Once the product has reaches a low heating value, as it inevitably will at some point in the operation, that production hole is capped off and the product gas is then forced to pass through the seam to the next production borehole, some 75 feet (23 m) away. This new path has already been prepared by previous backward burning operations. Schematics of this approach will be discussed later in Section 7. More details on design and operating features of underground coal gasification are provided in Section 6.

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UTILIZATION ALTERNATIVES

Low Btu Gas

Two general types of product gases can be produced using underground coal gasification. If air is used as the gasifying agent, a low Btu gas results, with heating value ranging from 90 Btu/SCF (3.35 MJ/m^3) to 160 Btu/SCF (6.0 MJ/m^3). A medium Btu gas is produced by gasification with oxygen, yielding a heating value of 200 to 350 Btu/SCF (7.5 to 13.0 MJ/m^3). The main difference between the two gases lies in the presence or absence of the diluent nitrogen. By enriching air with variable amounts of oxygen, almost any heating value between 100 and 350 Btu/SCF (3.7 and 13.0 MJ/m^3) can be realized.

Product gas from an air-blown gasifier will ordinarily be used in power production. The power production step can consist simply of adding low Btu gas to a boiler burning a solid fuel (e.g., lignite). This configuration is feasible in Texas because there are eleven mine-mouth lignite fueled power plants scheduled to be in operation on the lignite belt by 1985. In situ gasification sites could be located close to those areas where strip mining and power production simultaneously occur, since the deep basin lignite lies down-dip in the same formation from the near surface lignite. The advantage of blending solid and gaseous fuel is that the gaseous fuel can be introduced intermittently, hence low Btu gas does not alone have to provide the base load. This type of fuel scheduling would help alleviate the uncertainty regarding the capability of UCG to provide continuous production of a relatively constant heating value gas. Historically, consistent gas production (both rate and heating value) has not always been achieved. If low Btu gas were used in a conventional gas-fired furnace without a supplemental fuel, serious derating of boiler efficiency would result [7]. This derating arises because of the larger sensible heat losses and pressure losses, resulting from the high nitrogen content of the gas. Such derating is insignificant when mixed fuels such as coal/gas are employed.

Proponents of UCG argue that a reliable, first generation technology based on air gasification has been demonstrated in the Soviet Union. Corroborating evidence is available in U. S. field tests. Therefore it is conceivable that UCG could be used to provide the fuel for a base-load combined cycle plant. Such a plant using surface gasification technology (See Figure 2) will be demonstrated by the Electric Power Research Institute and the U. S. Department of Energy in the mid-1980's [8]. The use of gasification with a combined cycle plant is advantageous compared to conventional coal combustion followed by stack gas cleaning for two main reasons:

(1) More cost effective pollution control for emissions of sulfur and nitrogen oxides and particulates, due to the gasification and gas cleanup steps.
(2) Higher overall power cycle efficiency, due to the use of both gas and steam turbines [9].

It should be pointed out that UCG has been demonstrated at pressures of about 3 atmospheres or less, hence some reduction in power cycle efficiency

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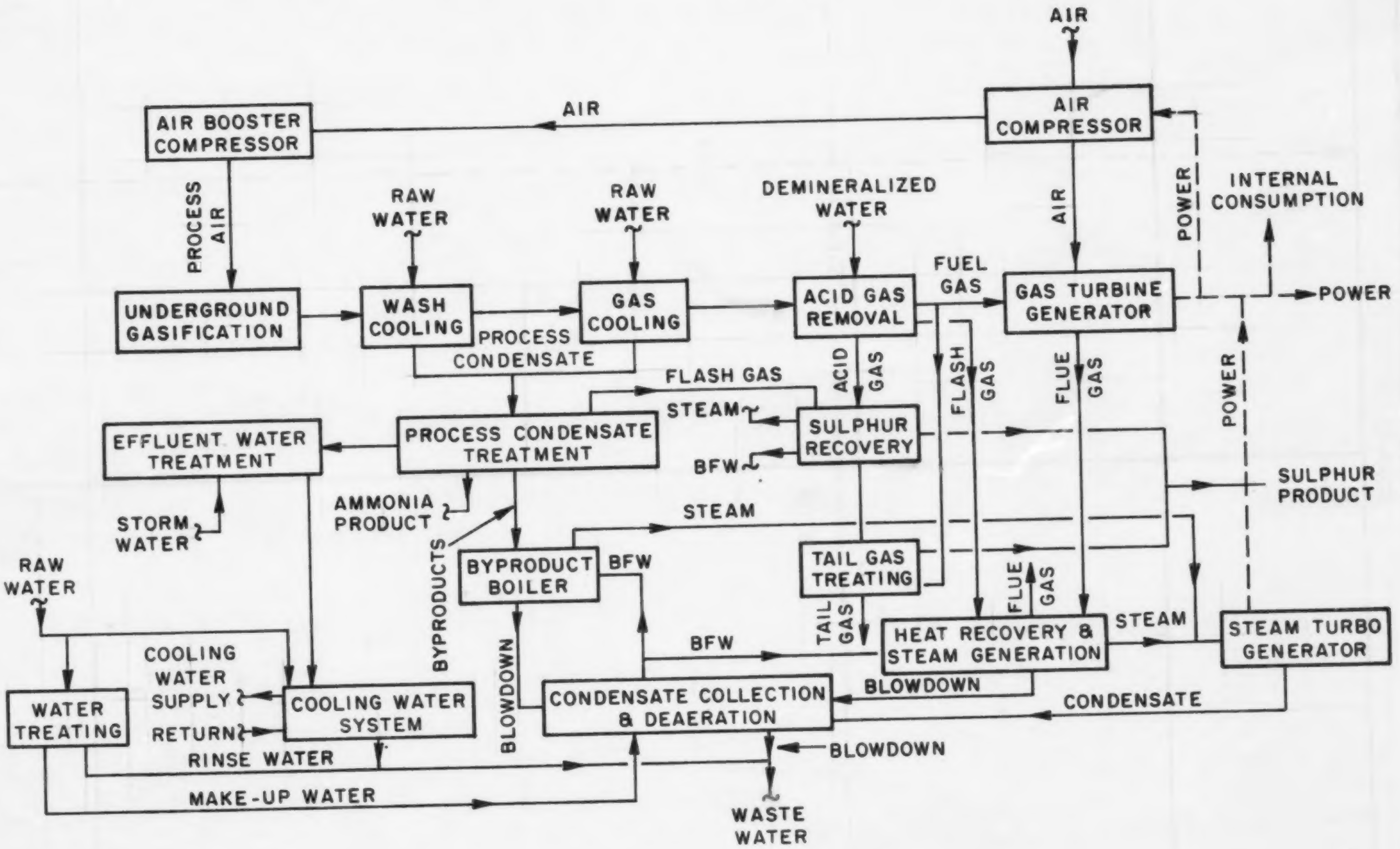
AIR
AIR COMPRESSOR
AIR
AIR BOOSTER COMPRESSOR
AIR
POWER
INTERNAL CONSUMPTION
POWER
PROCESS AIR
RAW WATER
RAW WATER
DEMINERALIZED WATER
FUEL GAS
UNDERGROUND GASIFICATION
WASH COOLING
GAS COOLING
ACID GAS REMOVAL
GAS TURBINE GENERATOR
PROCESS CONDENSATE
ACID GAS
FLASH GAS
FLUE GAS
POWER
FLASH GAS
STEAM
SULPHUR RECOVERY
BFW
EFFLUENT WATER TREATMENT
PROCESS CONDENSATE TREATMENT
SULPHUR PRODUCT
STORM WATER
AMMONIA PRODUCT
STEAM
BYPRODUCTS
BYPRODUCT BOILER
BFW
TAIL GAS TREATING
FLUE GAS
RAW WATER
TAIL GAS
STEAM
BFW
HEAT RECOVERY & STEAM GENERATION
STEAM TURBO GENERATOR
COOLING WATER SUPPLY
RETURN
COOLING WATER SYSTEM
BLOWDOWN
CONDENSATE COLLECTION & DEAERATION
BLOWDOWN
CONDENSATE
WATER TREATING
RINSE WATER
BLOWDOWN
MAKE-UP WATER
WASTE WATER

Figure 2. UCG - Combined Cycle Power Plant

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will result compared to surface gasification (the gasifier shown in Figure 2 is operated at 20 atm or 2.03 mPa.). In the long run it appears that improved thermal efficiencies available from combined cycle systems combined with the steadily decreasing domestic supplies of oil and gas will cause the low Btu gasification/combined cycle method of generating electricity from coal to gain acceptance by utilities. Under existing technology, such a fuel cycle is comparable in thermal efficiency (about 35%) to the conventional approach (with stack gas cleaning), but it requires a much larger capital investment and is more complex operationally. However, technological improvements in turbine design by the 1990's should allow an increase in allowable turbine operating temperatures, increasing thermal efficiency sufficiently to offset the additional capital required for coal gasification. Ultimately the overall efficiency might exceed 42% [9].

One concern about the use of UCG with combined cycle technology is that a gas with heating values around 100 Btu/SCF (3.7 MJ/m^3) is not suitable for reasonable efficiencies, while 150 Btu/SCF (5.5 MJ/m^3) is acceptable. U. S. field tests with air have achieved the latter value in some locations (such as the Hanna, Gulf, and ARCO tests on sub-bituminous coal), but the preponderance of the U. S. and Soviet field data for heating values obtained by gasification of lignite with air are at the lower end of the spectrum. Therefore unless further field tests with air injection demonstrate that a high quality gas can be obtained reproducibly, then the combined cycle option must be considered to be less attractive for use in Texas than other alternatives discussed here.

Medium Btu Gas

If oxygen is injected in the coal seam for gasification, the resulting medium Btu gas could be used directly in a conventional gas-fired boiler with negligible derating (vs. natural gas). However, the economics of this approach are not as attractive as for air injection, mainly due to the cost of an oxygen plant. One exeption to this statement may be in small industrial gas-fired heaters, although it is difficult to draw any conclusions at this time. The main use of medium Btu gas from UCG will probably be to produce a feedstock to replace natural gas and oil, both of which ultimately will be in short supply. Figure 3 illustrates a general processing flowsheet for chemical production from UCG, which is analogous to that for surface gasification technology. Methanol seems to be an attractive product because it can be used directly as a fuel or converted with high selectivity to gasoline using the Mobil-M process [10]. Table 1 lists the general steps for the treatment of the crude low or medium Btu gas [11]. Depending upon the product desired, some of the process steps listed may not be required at all, or they may be required on a smaller scale. For example, in the raw gas upgrading section, step 4 may be deleted if methane is not a principal product.

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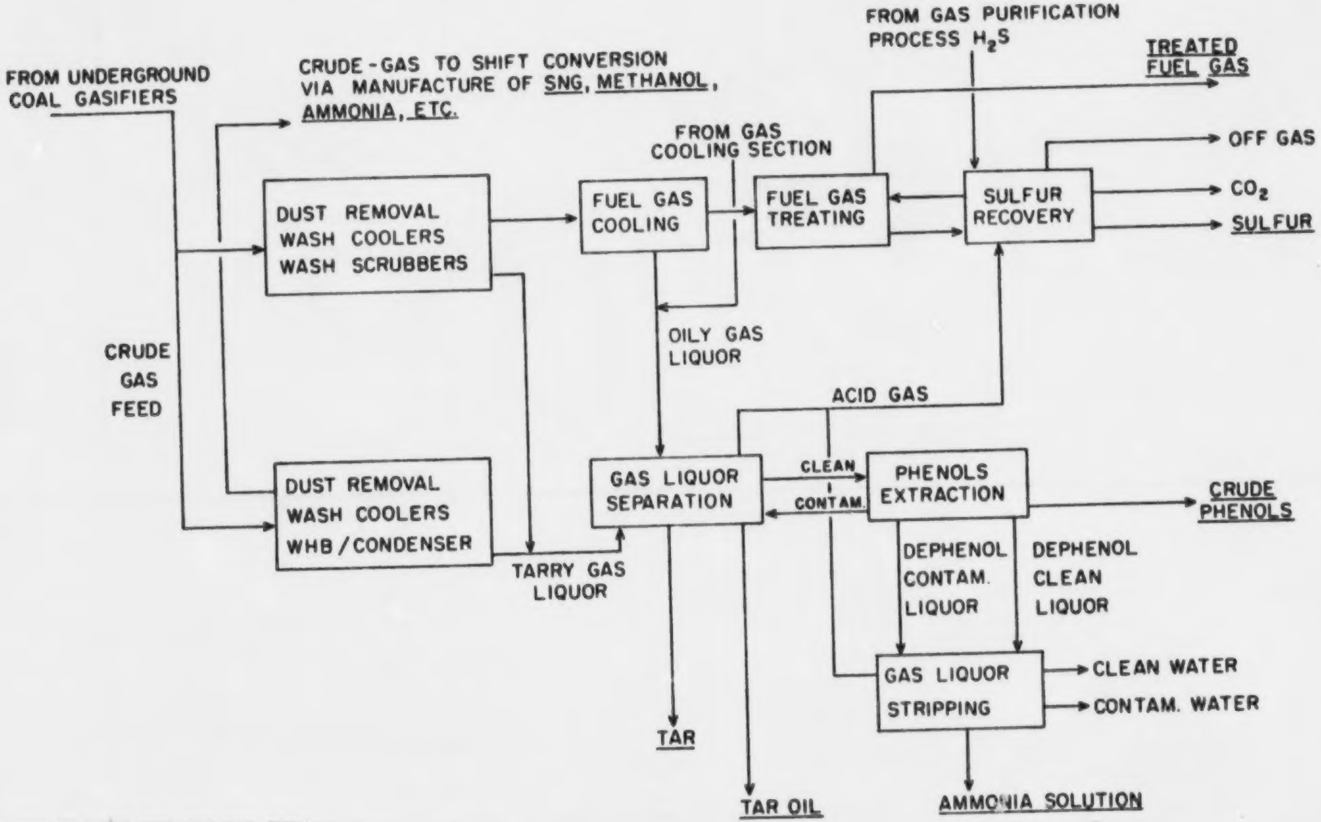
FROM UNDERGROUND COAL GASIFIERS
CRUDE-GAS TO SHIFT CONVERSION VIA MANUFACTURE OF SNG, METHANOL, AMMONIA, ETC.
FROM GAS PURIFICATION PROCESS H2S
TREATED FUEL GAS
FROM GAS COOLING SECTION
DUST REMOVAL WASH COOLERS WASH SCRUBBERS
FUEL GAS COOLING
FUEL GAS TREATING
SULFUR RECOVERY
OFF GAS
CO2
SULFUR
CRUDE GAS FEED
OILY GAS LIQUOR
ACID GAS
DUST REMOVAL WASH COOLERS WHB/CONDENSER
GAS LIQUOR SEPARATION
CLEAN
CONTAM.
PHENOLS EXTRACTION
CRUDE PHENOLS
TARRY GAS LIQUOR
DEPHENOL CONTAM. LIQUOR
DEPHENOL CLEAN LIQUOR
GAS LIQUOR STRIPPING
CLEAN WATER
CONTAM. WATER
TAR
TAR OIL
AMMONIA SOLUTION

Figure 3. Simplified Process Flow Diagram for Production of Chemicals from Underground Coal Gasification

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Table 1. Principal Process Features in the Treatment of Crude Gas Produced by Underground Gasifiers

Plant Section	Process Steps
Gas cleanup and heat recovery	1. Raw gas quench; dust removal
	2. Heat recovery; tarry gas liquor condensation and separation
Raw gas upgrading	1. Shift conversion
	2. Gas cooling
	3. Acid gas removal
	4. Methanation
	5. Compression and dehydration
Effluent treatment	1. Gas liquor separation
	2. Extraction of phenols
	3. Gas liquor stripping
	4. Sulfur recovery
Supporting utilities	1. Oxygen plant
	2. Steam generation
	3. Electric power generation
	4. Other utility support systems

It must be emphasized that the processes described above are conceptual, and the product gas composition, pressure, and desired final product fix the conditions of the aboveground processing.

The effluent from underground gasifiers may contain, in addition to ash and coal fines, some coal carbonization products (e.g., tar, oil naphtha, phenolics, and ammonia). Basically, crude gas cleanup will have to be

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provided to remove entrained solids, quench the gas, scrub it to remove tars and other condensables, and recover heat where feasible. The carbonization products may be used as plant fuel. Based on UCG field data, a small (less than 5 percent) fraction of the energy production appears as liquid byproducts.

In processing the crude gas it may be desirable to shift the CO produced to H_2, in order to minimize transportation costs; another possibility is to remove H_2 from the product gas stream. Several methods are available, including hydrogen purification by a hollow fiber membrane process. This process involves hydrogen permeation through polymeric materials capable of removing hydrogen from a hydrocarbon gas mixture [11].

One of the serious impediments to handling low or medium Btu gas is that it is not as concentrated an energy form as methane; in the case of medium Btu gas, the cost of transportation over that of methane is inversely proportional to the ratio of heating values, or about 3.3. However, this cost may be manageable for transport distances of 100 miles (160 Km) or less, i.e., about \$.20 per 10^6 Btu (\$.19 per GJ). However, if the product gas can be converted to hydrogen, much lower line pressure drops are required because of hydrogen's lower density and viscosity. On equivalent bases of energy delivered, a hydrogen pipeline is slightly more expensive than one for methane. There are more serious operational questions raised by hydrogen pipelines, as described by Dickson et al. [12]. Hydrogen embrittlement of the pipe and gas leakage are the major concerns. While there have been some laboratory studies on the problem, proven designs are not yet available, especially for high pressure lines. A low pressure pipeline in Germany has been distributing hydrogen for 30 years with no serious problems.

ENVIRONMENTAL ASPECTS OF UNDERGROUND COAL GASIFICATION

One of the major obstacles to commercialization of underground coal gasification in the U. S. is the lack of knowledge of the environmental impact of this technology. Soviet field data reported in the literature has focused mainly on gas production; there is very little information on environmental effects. Presently there are several major efforts to quantify the environmental effects of UCG field tests. It is important that as this technology nears commercialization, the possible environmental problems should be accurately defined and solutions proposed and tested. In addition, the specific application of UCG in Texas should be reviewed, since it will undoubtedly be the site of one of the first commercial ventures.

In situ gasification overcomes many of the objectionable environmental features of strip and deep mining. The sulfur in the lignite is principally converted to hydrogen sulfide, which is readily removed from the product gas stream. Air emissions from in situ gasification are qualitatively similar to those for surface gasification. Pollution by solid waste is reduced, since inert ash material is left underground. Massive excavation of the overburden is avoided, although the close well spacing does create some surface damage, and surface subsidence is possible. Most significant, UCG does present

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water pollution problems for the subsurface environment.

This report analyzes in detail the environmental effects arising out of projected large scale use of underground coal gasification in Texas. The report is divided into five major sections:

(1) Resources - This section entails identification of the location, quality, and quantity of lignites and which areas of Texas are likely for commercial development using UCG technology. Using an exploration model developed over the past eight years, new estimates of deep basin lignite resources are classified by geologic unit and geography. Formations evaluated include the Wilcox, Yegua, and Jackson. Resources have been defined in terms of seams at least five feet in thickness and with 2000 feet (600 m) or less of cover, which are realistic near-term conditions for in situ gasification.

The Wilcox is not only an important lignite-bearing unit, but is an important aquifer in Texas. The Yegua and Jackson are only locally aquifers. Fresh water is found at up to 3000 feet (900 m) below the surface in parts of the Wilcox. Gasification in many instances will take place in the freshwater column posing a threat to water quality. Base-line environmental data have been compiled by geologic unit and geographic region to establish where the best quality water occurs. In areas of superior water quality and high water productivity, gasification should proceed more cautiously.

Geology and hydrology are critical parameters for the selection of in situ gasifiers. The essential elements of an ideal site include resources in thick seams, continuous seams of uniform thickness with simple internal stratigraphy, seams roofed and floored by thick mud, sand-poor host ground, proximity to a recharge area, aquifers oriented perpendicular to groundwater flow directions, formation waters of high TDS, and structural simplicity. The Wilcox, Yegua, and Jackson geologic units have been tested against the criteria of the ideal gasifier and location relative to energy demand points to identify potential gasifier sites. On this basis predictions have been made about where in situ gasification is likely to impact the Texas environment.

(2) Engineering and Geological Factors in Underground Coal Gasification - The effect of geological conditions on operation of underground coal gasification facilities is significant, and includes such variables as water influx, roof collapse, well geometry/spacing, sweep efficiency, seam thickness, gas leakage, gas heating value, and production pressure. The interrelationship of these parameters is discussed along with their environmental implications. In addition, the

impact of oxygen vs air gasification is considered in this section. A predictive model for gas composition is used in order to evaluate expected heating values for various process conditions.

(3) Environmental Impacts from Underground Coal Gasification - The potential impacts to the environment from UCG include air, land, and water. Limited data are available from field tests in the U.S.A. and U.S.S.R., which permits preliminary analysis of the impacts. Of main concern are the high concentrations of organics, ammonia, sulfate, and total dissolved solids, which appear in the cavity created by gasification. Most of the inorganic contaminants arise from leaching of ash, while organics and ammonia are deposited on surrounding strata via condensation when the product gases are cooled underground.

Air pollutants may arise from above-ground processing of the gas, although these emissions are not as serious as subsurface water pollution. Impacts upon land are not well-quantified at this time but are not a significant drawback of UCG. Surface subsidence may occur during a commercial operation but has not been noticeable for most small-scale field tests performed in the U.S.A.

In this section, we review:

(a) The applicability of existing environmental regulations to each impact class (water, air, land).
(b) The available literature and data to identify the nature and magnitude of the impact (e.g., contaminants released to water or air).
(c) How these impacts can be mitigated through design and operation of the UCG facility.

(4) Subsurface Pollutants Transport and Migration - Knowledge on how potential pollutants might be transported underground must be obtained prior to formulation of restoration strategies for a given site. The prediction of subsurface migration must be accomplished by acquisition of information on subsurface structure and geology; this information can then be used to build mathematical models for groundwater flow and pollutant dispersion. In this section we summarize the types of models that could be used for predictive purposes and identify the areas where improved modeling is needed.

(5) Restoration and Pollutant Control of UCG Sites - Guidelines for restoration of UCG sites are not yet finalized, and the difficulties of formulating specific regulations for every UCG site are discussed. Suggestions for restoration criteria are advanced, along with an analysis of monitoring data from selected field sites. Control technologies which might be used to abate or minimize adverse water quality impacts are

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proposed.

The final section of the report lists the major conclusions of the study. Also summarized are the areas where further research and data are needed, since at the present time only a preliminary evaluation of the environmental impact of underground coal gasification in Texas can be made.

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SECTION 5

RESOURCES OF DEEP-BASIN LIGNITE IN TEXAS

GEOLOGIC SETTING

Texas lignite occurs in three Eocene (lower Tertiary) geologic units - the Wilcox Group, Yegua Formation, and Jackson Group (Table 2) - and in three ancient depositional systems - fluvial, deltaic, and strandplain/lagoonal. Cyclic deposition is the fundamental style of sedimentation in the Texas Eocene. The motif is an alternation of regressive, thick fluvial-deltaic units such as the Wilcox and transgressive, thin fossiliferous, marine units such as the Weches (Figure 4). These units outcrop as belts in the inner Texas Coastal Plain and extend deep into the subsurface dipping 1° 2° Gulfward until, for example, the Wilcox is found at 10,000 feet (3,050 m) or more below the surface at Houston. The Wilcox and Jackson Groups are the most important lignite-bearing units. Depositional setting has been established from regional lithofacies maps (sand-percent, net-sand, maximum-sand) and lignite occurrence maps made from approximately 4,000 geophysical logs. An exploration model, built upon the relationship between sand-body geometry and lignite occurrence, has been developed for Texas lignite. The model is facies dependent and permits resource estimation where data are meager. In fluvial facies tracts low-sand areas and abundant lignite overlap whereas in deltaic and strandplain/lagoonal tracts high-sand areas and abundant lignite overlap [13].

In the Wilcox Group of east-central and east Texas, straight-, dendritic-, and bifurcating-channel geometries are displayed (Figure 5). Lignite at exploitable depths of 20 to 2,000 feet is a component facies of ancient fluvial depositional systems. Sites of accumulation were ancient hardwood swamps located in interchannel basins established by bounding alluvial ridges. Thus, regionally lignite occurrences are elongate parallel to major channel sand belts and the paleoslope (Figure 6). Lignite occurrences are projected up and down paleoslope between and parallel to sand belts to make resource estimates in areas of sparse data.

The Jackson Group of east Texas is characterized by a lobate sand-body geometry typical of deltas (Figure 7). Lignite is of deltaic origin and represents marsh accumulation in lower delta-plain environments. Lignites are postulated to represent ancient blanket peats which spread across a foundering delta surface. Regionally, lignite occurrences are lobate as well and mirror the sand-body geometry (Figure 8). Lignite projection is made with confidence on individual delta lobes into areas of sparse data.

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TABLE 2. Stratigraphic occurrences of Texas Lignite

		North of Colorado	South of Colorado River
OLIGOCENE		Catahoula Formation	
	Jackson Group	Whitsett Formation Manning Formation[a] Wellborn Formation Caddell Formation	lower Jackson[a]
EOCENE SERIES	Claiborne Group	Yegua Formation[a] Cook Mountain Formation Stone City Formation Sparta Sand Weches Formation	Laredo Formation
		Queen City Sand	El Pico Clay
		Reklaw Formation	Bigford Formation
	Wilcox Group	Calvert Bluff Formation[a] Simsboro Sand undivided Wilcox[a] Hooper Formation	lower Wilcox[a]
		Midway Group	

[a]principal lignite-bearing units

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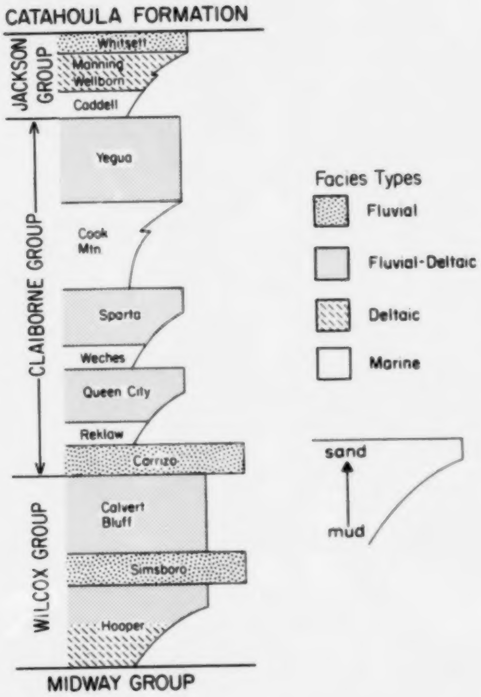
CATAHOULA FORMATION
JACKSON GROUP
Whitsett
Manning
Wellborn
Caddell
CLAIBORNE GROUP
Yegua
Cook Mtn
Sparta
Weches
Queen City
Reklaw
Carrizo
WILCOX GROUP
Calvert Bluff
Simsboro
Hooper
MIDWAY GROUP
Facies Types
Fluvial
Fluvial-Deltaic
Deltaic
Marine
sand
mud

Figure 4. Cyclic Deposition in the Texas Eocene (Kaiser et al. [13])

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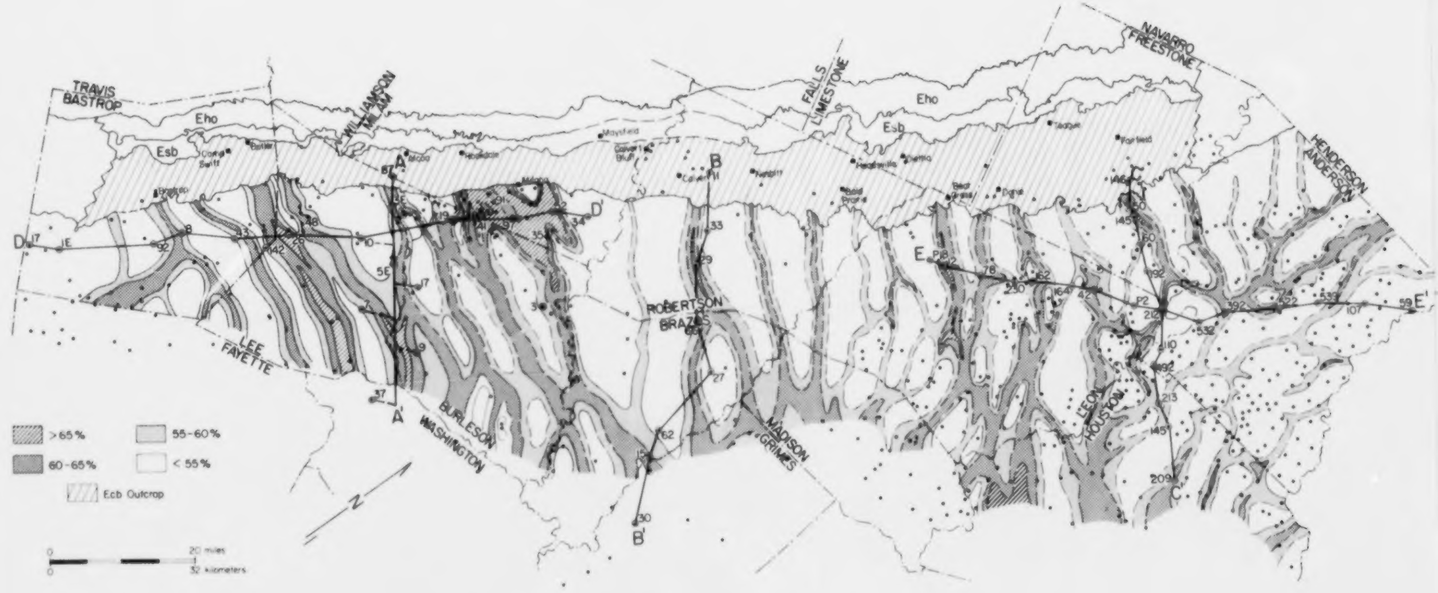
TRAVIS
BASTROP
WILLIAMSON
MILAM
FALLS
LIMESTONE
NAVARRO
FREESTONE
HENDERSON
ANDERSON
LEE
FAYETTE
BURLESON
WASHINGTON
ROBERTSON
BRAZOS
MADISON
GRIMES
LEON
HOUSTON
Eho
Esb
A
A'
B
B'
D
D'
E
E'
>65%
60-65%
55-60%
< 55%
Ecb Outcrop
N
0
20 miles
0
32 kilometers

Figure 5. Sand-percent Map of the Calvert Bluff Formation (Wilcox) in East-Central Texas (Kaiser [14])

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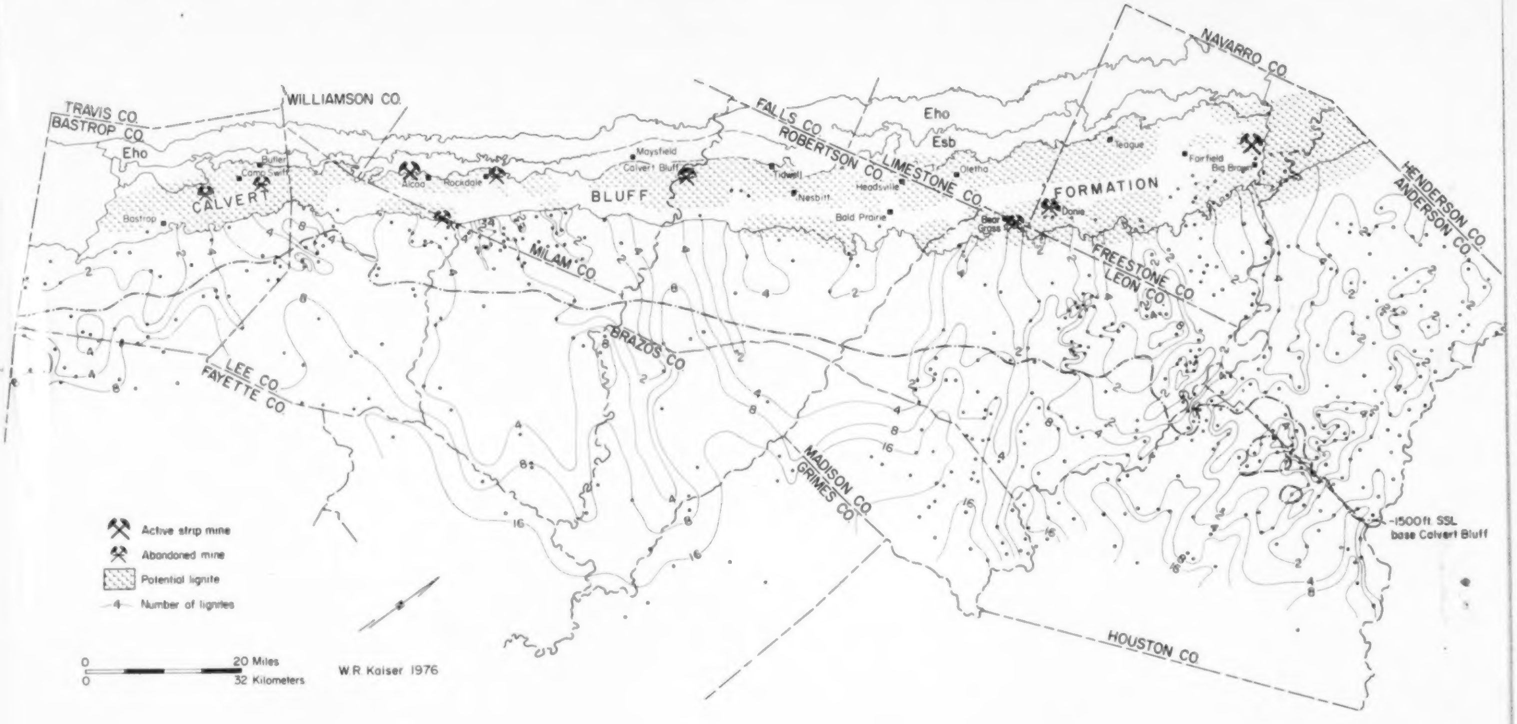
TRAVIS CO.
BASTROP CO.
WILLIAMSON CO.
FALLS CO.
ROBERTSON CO.
LIMESTONE CO.
NAVARRO CO.
HENDERSON CO.
ANDERSON CO.
FREESTONE CO.
LEON CO.
MILAM CO.
BRAZOS CO.
LEE CO.
FAYETTE CO.
MADISON CO.
GRIMES CO.
HOUSTON CO.
Eho
Esb
CALVERT
BLUFF
FORMATION
Bastrop
Butler
Camp Swift
Alcoa
Rockdale
Maysfield
Calvert Bluff
Tidwell
Nesbitt
Headsville
Bald Prairie
Oletha
Bear Grass
Donie
Teague
Fairfield
Big Brown
-1500 ft SSL base Calvert Bluff
Active strip mine
Abandoned mine
Potential lignite
Number of lignites
0 20 Miles
0 32 Kilometers
W.R. Kaiser 1976
2
4
8
16
34

Figure 6. Occurrence of Deep-Basin Lignite in the Calvert Bluff Formation (Kaiser [14]). Lignite identified from electric logs using operational definition, shown by isopleths (number of lignites).

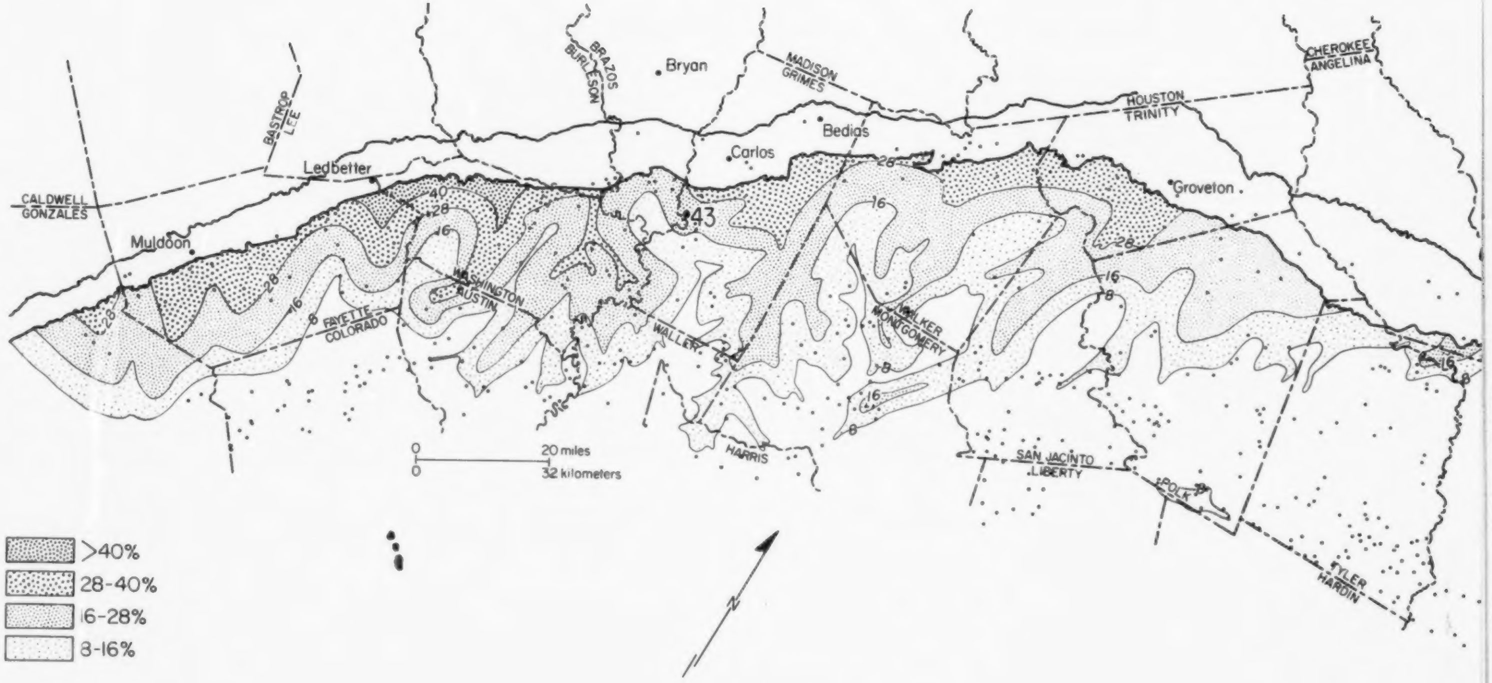
CHEROKEE
ANGELINA
HOUSTON
TRINITY
Groveton
MADISON
GRIMES
Bedias
Bryan
BRAZOS
BURLESON
Carlos
BASTROP
LEE
Ledbetter
CALDWELL
GONZALES
Muldoon
WASHINGTON
AUSTIN
FAYETTE
COLORADO
WALLER
WALKER
MONTGOMERY
HARRIS
SAN JACINTO
LIBERTY
POLK
TYLER
HARDIN
43
40
28
16
8
0
20 miles
32 kilometers
>40%
28-40%
16-28%
8-16%

Figure 7. Sand-Percent Map of the Jackson Group in East Texas, Exclusive of the Whitsett Formation (Kaiser et al., [13])

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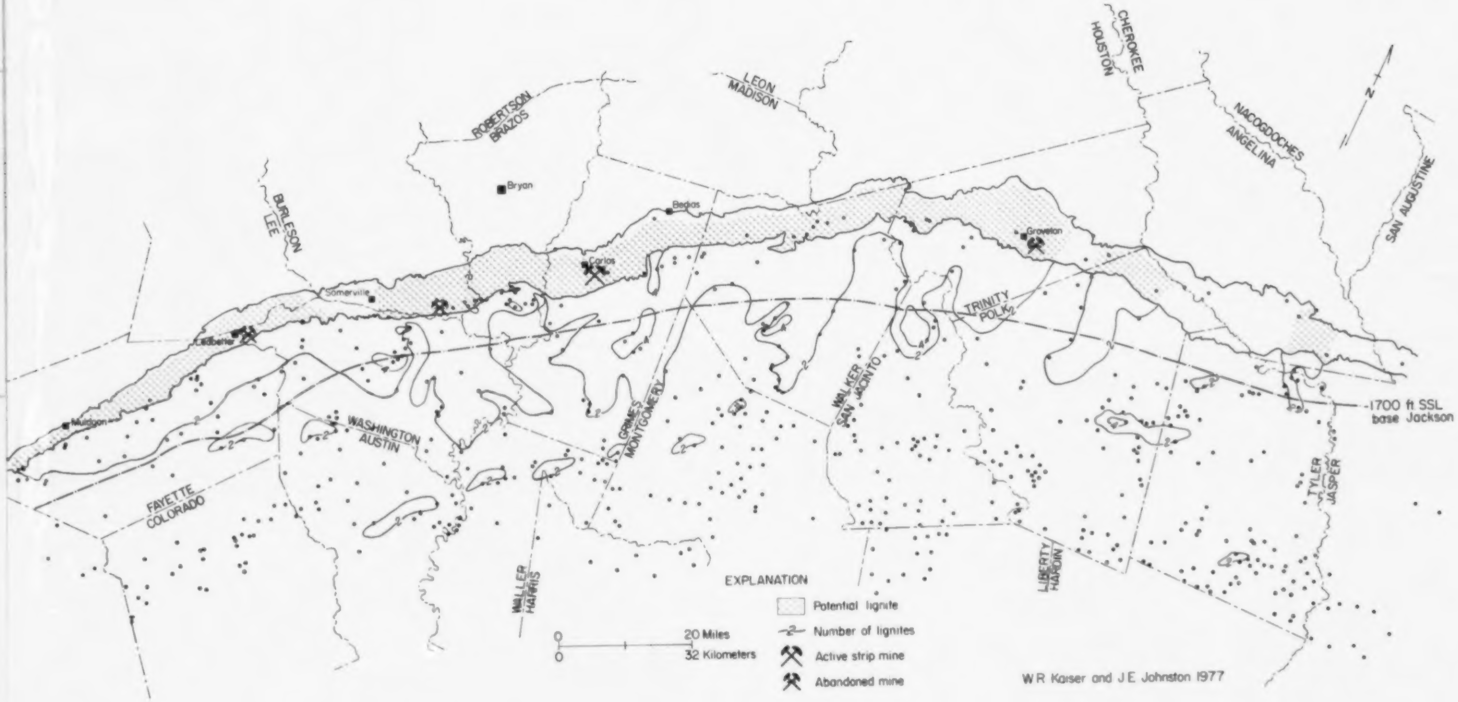
ROBERTSON
BRAZOS
LEON
MADISON
CHEROKEE
HOUSTON
NACOGDOCHES
ANGELINA
SAN AUGUSTINE
N
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LEE
Bryan
Bedias
Groveton
Carlos
Somerville
Ledbetter
Muldoon
TRINITY
POLK
WALKER
SAN JACINTO
GRIMES
MONTGOMERY
WASHINGTON
AUSTIN
FAYETTE
COLORADO
WALLER
HARRIS
LIBERTY
HARDIN
TYLER
JASPER
2
-1700 ft SSL base Jackson
EXPLANATION
Potential lignite
Number of lignites
Active strip mine
Abandoned mine
0
20 Miles
0
32 Kilometers
W.R. Kaiser and J.E. Johnston 1977

Figure 8. Occurrence of Deep-Basin lignite in the Jackson Group (Manning and Wellborn Formations) in East Texas (Kaiser et al., [13])

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Jackson lignite in south Texas is associated with linear sand bodies oriented approximately normal to paleoslope and parallel to depositional strike (Figure 9). Lignite occurs topping ancient strandplain/barrier-bar beach sequences. Regionally, lignite occurrences are elongate and coincide with maximum sand development (Figure 10). Projection of this trend is easily made into data poor areas.

RESOURCE ESTIMATION

Deep-basin lignite resources between 200 and 5,000 feet (61 to 1,525 m) were estimated in 1974 by Kaiser [1] at approximately 100 billion short tons. All seams were assumed to be 2 feet (0.6 m) thick and laterally continuous. Based on present knowledge,resources defined in terms of seams greater than 5 feet (1.5 m) thick and between 200 and 2,000 feet (61 and 610 m) are more realistic for in situ gasification. Resources have been calculated here in those terms and in the context of a superior understanding of the regional geology. The estimate rests on a data base of 3,620 electric and induction logs run in oil and gas wells (Table 3).

Identification of Lignite

In the absence of porosity logs such as density or neutron, lignite is operationally defined as a bed with a sharp resistivity spike and a baseline or shale spontaneous potential (SP) [1]. The operational definition becomes increasingly more difficult to apply as formation waters become fresher and the SP less well defined. Therefore, lignites become increasingly more difficult to identify moving updip from the deep basin into the shallow subsurface shere they cannot be easily distinguished from thin, fresh-water sands. In this case the exploration model as outlined above is used to project lignite updip from the deep basin into the shallow subsurface.

Lignites are most easily identified on electrical logs. Opposite a lignite seam the lateral curve has an extremely peaked resistivity kick; this curve will identify lignites as thin as 1 foot (0.3 m). The long normal curve (64 inche spacing) displays a reversal toward the baseline in beds thinner than 64 inches (1.6 m) (Figure 11, well Q-30), thus providing a way to identify seams greater than 5 feet (1.5 m) thick. The induction log is not well suited to the identification of lignites less than 4 feet (1.2 m) thick; however, thicker beds can be identified reasonably well on curve peakedness (Figure 11, well Q-48).

Occurrence of Lignite

The occurrence of lignite in the deep basin is shown on a series of isopleth maps in which the total number of lignites, as defined operationally in the stratigraphic interval of interest, were mapped (Figures 6,8,10, 12,13,14). Also recorded were the number greater than 5 feet (1.5 m) thick. A structure contour map on the base of each interval was made and allows estimation of the drilling depth necessary to test all the lignite-bearing interval at any point in the basin. Only the minus 1,500 feet sub-sealevel (SSL) structure contour is shown on the occurrence maps. Maps for the Wilcox Group, Jackson Group, and Yegua Formation in east Texas were taken

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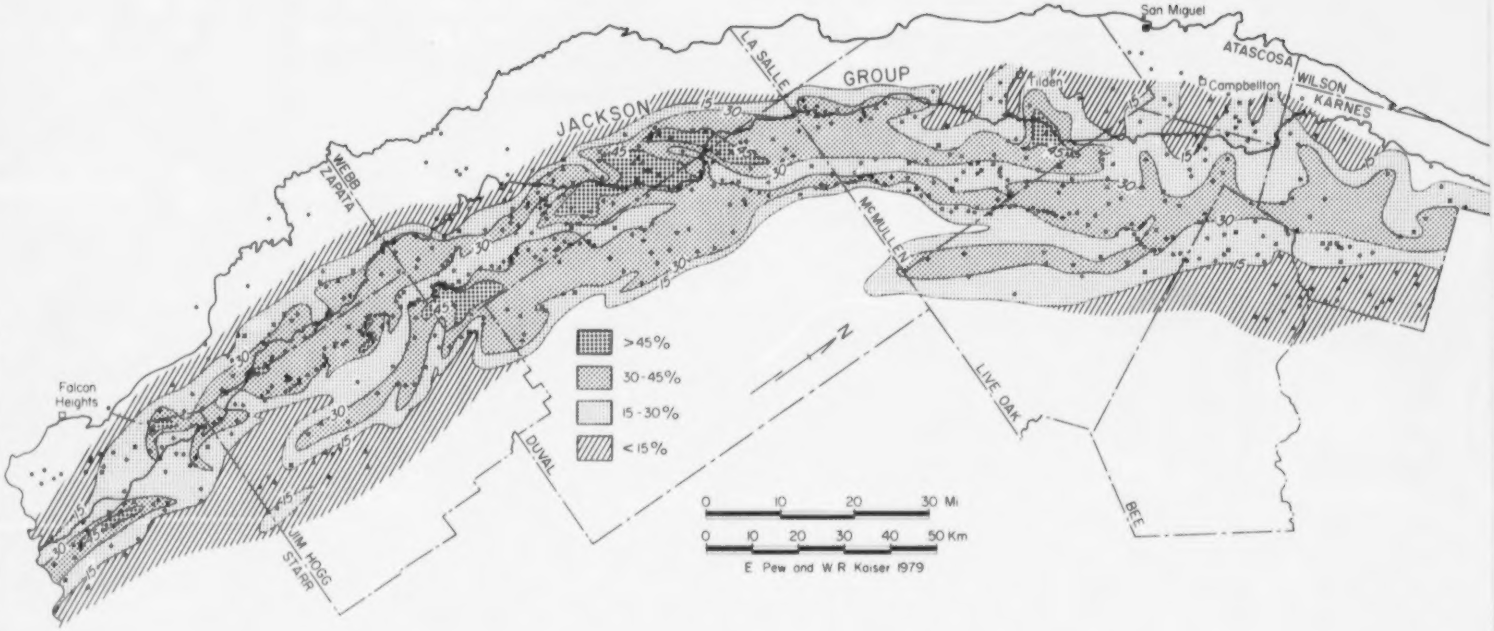
San Miguel
ATASCOSA
WILSON
KARNES
Campbellton
Tilden
GROUP
LA SALLE
JACKSON
McMULLEN
WEBB
ZAPATA
LIVE OAK
BEE
DUVAL
JIM HOGG
STARR
Falcon Heights
N
>45%
30-45%
15-30%
<15%
0 10 20 30 Mi
0 10 20 30 40 50 Km
E. Pew and W.R. Kaiser 1979
15
30
45

Figure 9. Sand-Percent Map of the Lower Part of the Jackson Group in South Texas

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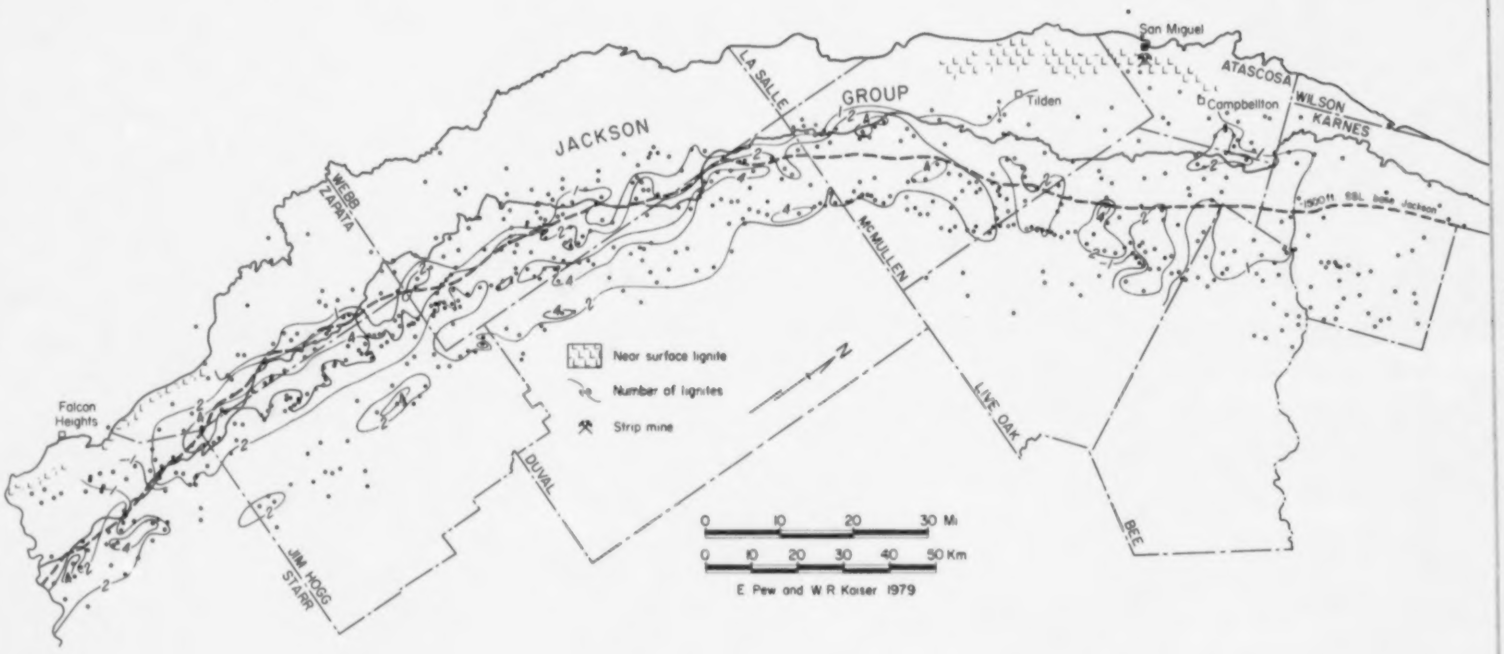
San Miguel
ATASCOSA
WILSON
KARNES
Campbellton
Tilden
GROUP
LA SALLE
JACKSON
WEBB
ZAPATA
McMULLEN
LIVE OAK
BEE
1500 ft SSL base Jackson
Falcon Heights
DUVAL
JIM HOGG
STARR
Near surface lignite
Number of lignites
Strip mine
N
0 10 20 30 Mi
0 10 20 30 40 50 Km
E Pew and W R Kaiser 1979

Figure 10. Occurrence of Deep-Basin Lignite in the Lower Jackson Group in South Texas

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	Wilcox east central	Wilcox north east	Wilcox Sabine Uplift	Wilcox south	Wilcox subtotal	Jackson east	Jackson south	Jackson subtotal	Yegua east	Total
x 10^6 short tons	10499	-0-	8814	4631	23944	5600	5275	10875	-0-	34819
percent	30	-0-	25	14	69	16	15	31	-0-	100
Data (E-logs)	626	506	396	363	1891	587	547	1134	595	3620

TABLE 3. Deep-Basin Resources in Texas (millions of short tons)

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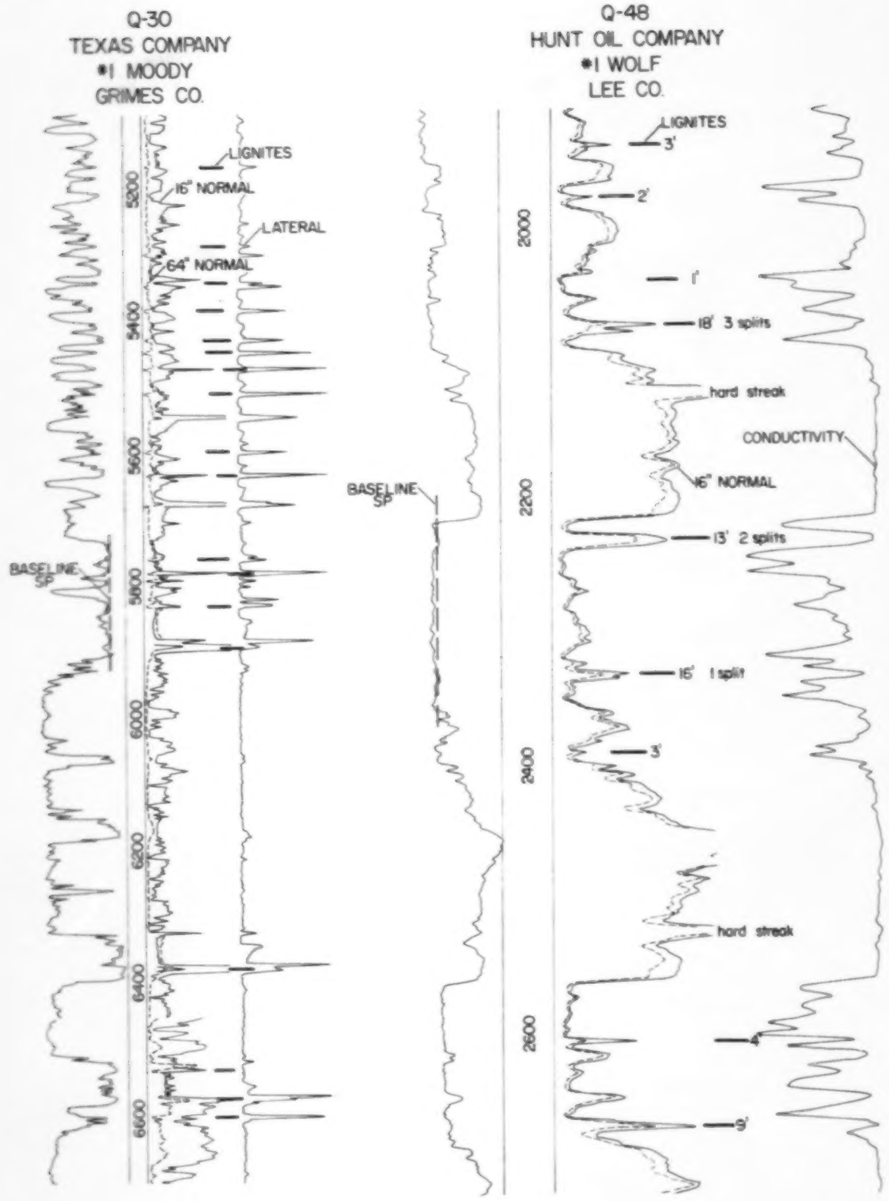

Figure 11. Lignite Response on an Electric Log (Q-30) and Induction Log (Q-48). Lignites on Q-48 identified from a Companion Neutron Log. See Figure 5 for Location of Logs. (Kaiser [14]).

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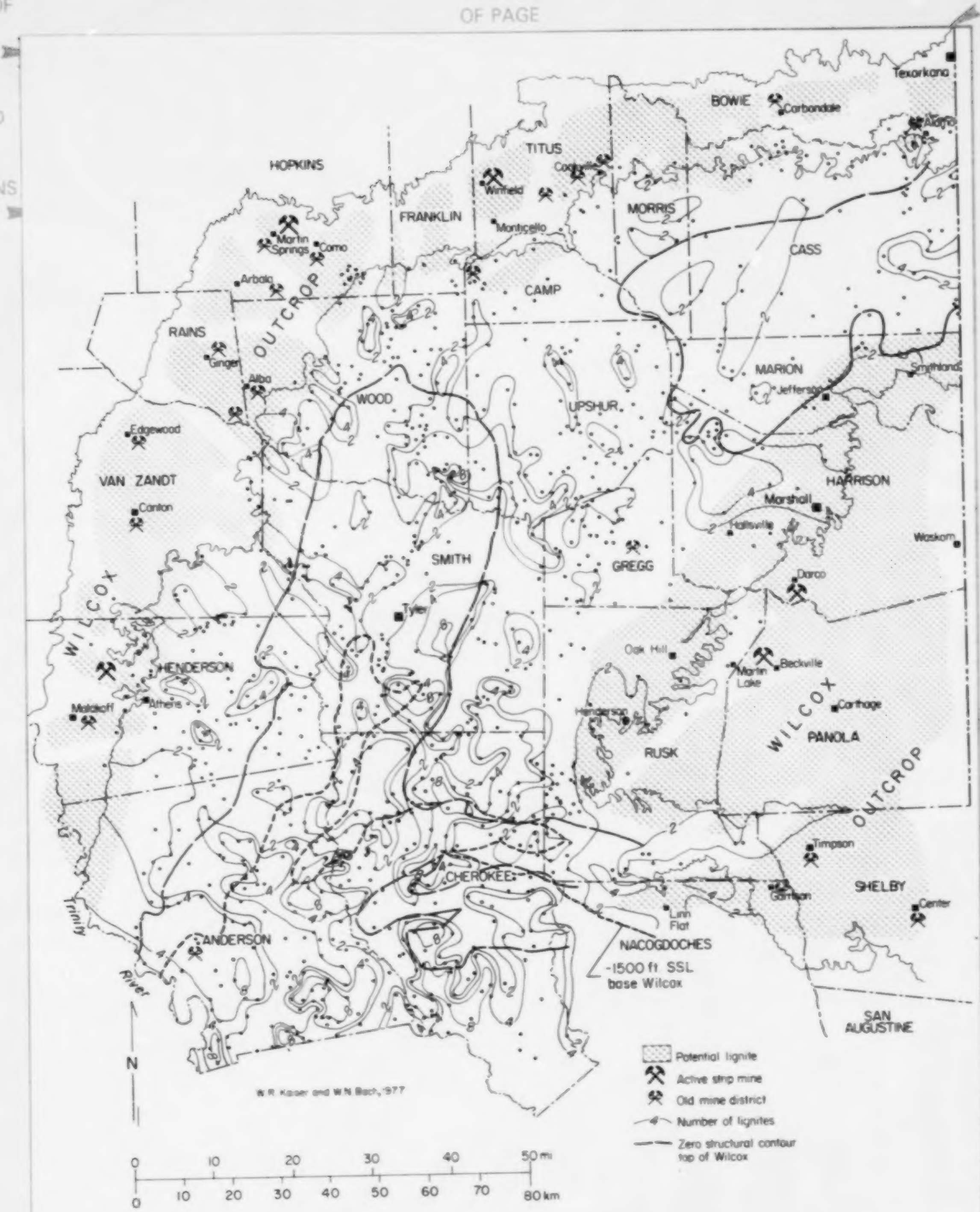
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Carbondale
TITUS
Cookville
Winfield
HOPKINS
Martin Springs
Como
FRANKLIN
Monticello
MORRIS
CASS
Arbala
CAMP
OUTCROP
RAINS
Ginger
Alba
WOOD
UPSHUR
MARION
Jefferson
Smithland
Edgewood
VAN ZANDT
Canton
HARRISON
Marshall
Hallsville
Waskom
SMITH
GREGG
Darco
WILCOX
Tyler
Oak Hill
Beckville
Martin Lake
HENDERSON
Athens
Malakoff
Henderson
Carthage
RUSK
WILCOX
PANOLA
OUTCROP
Timpson
SHELBY
CHEROKEE
Garrison
Center
Linn Flat
NACOGDOCHES
-1500 ft. SSL base Wilcox
ANDERSON
Trinity River
SAN AUGUSTINE
N
W.R. Kaiser and W.N. Bach, 1977
Potential lignite
Active strip mine
Old mine district
Number of lignites
Zero structural contour top of Wilcox
0 10 20 30 40 50 mi
0 10 20 30 40 50 60 70 80 km

Figure 12. Occurrence of Deep-Basin Lignite in the Undivided Wilcox Group in East Texas (Kaiser et al., [13])

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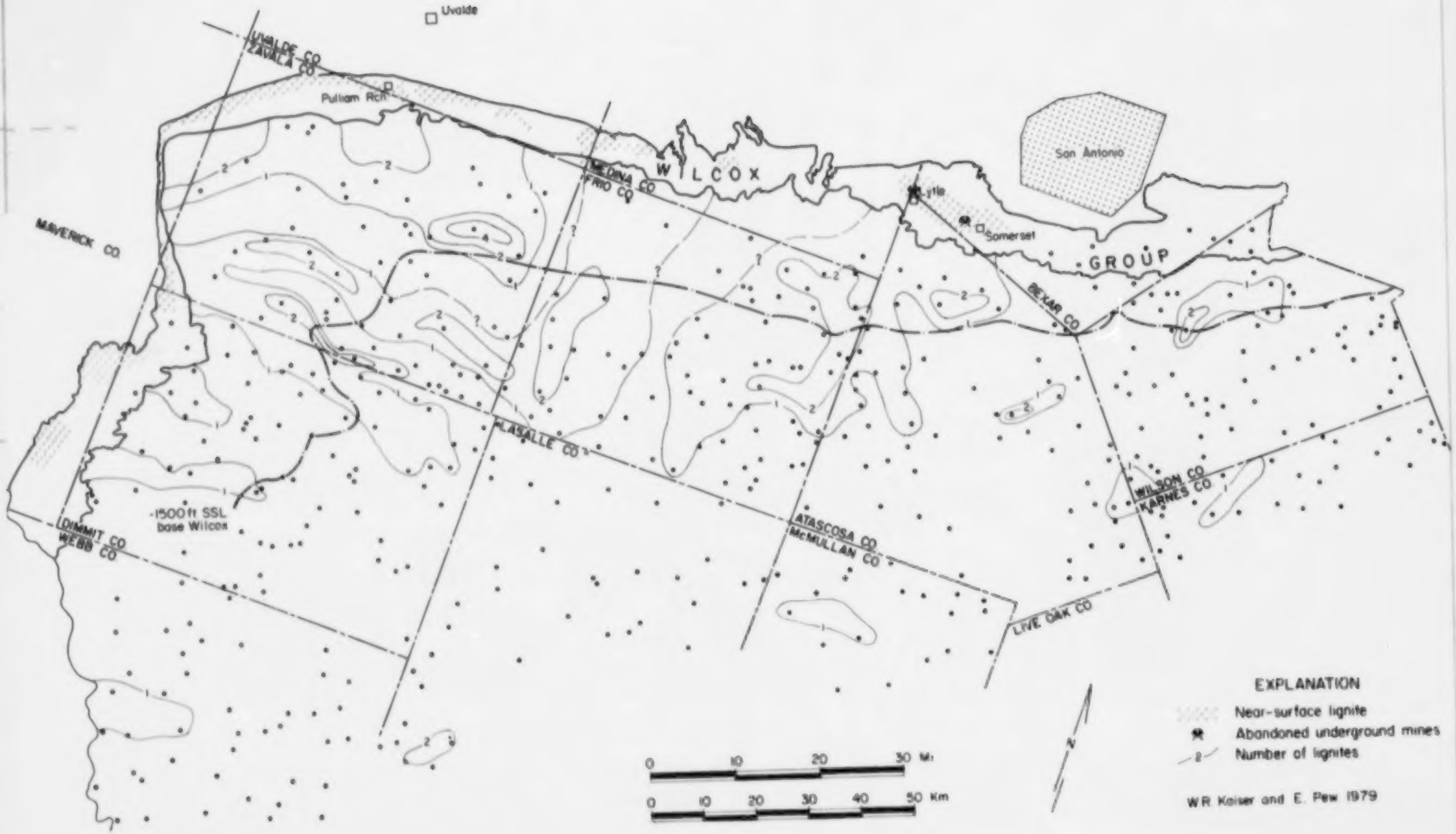
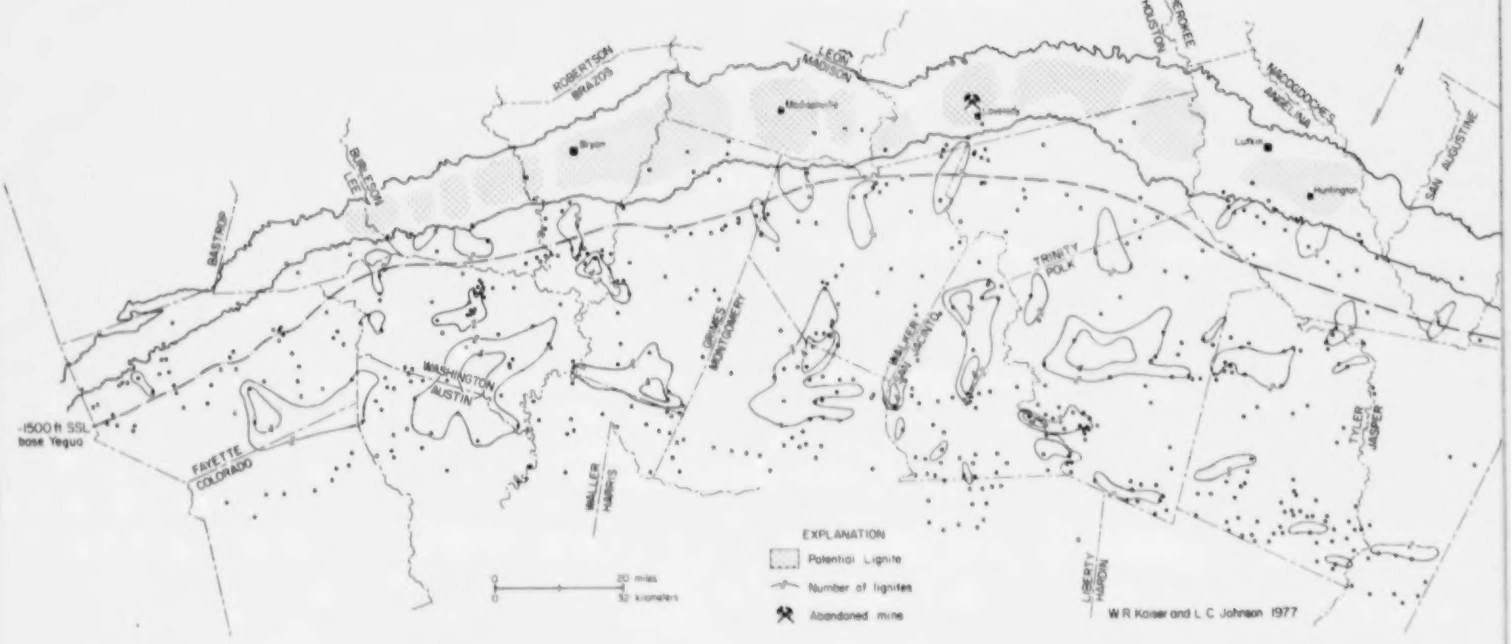

Uvalde
UVALDE CO
ZAVALA CO
Pulliam Rch
MEDINA CO
FRIO CO
WILCOX
GROUP
San Antonio
Lytle
Somerset
BEXAR CO
MAVERICK CO
LASALLE CO
ATASCOSA CO
McMULLAN CO
WILSON CO
KARNES CO
LIVE OAK CO
DIMMIT CO
WEBB CO
-1500 ft SSL base Wilcox
1
2
4
?
N
0 10 20 30 Mi
0 10 20 30 40 50 Km
EXPLANATION
Near-surface lignite
Abandoned underground mines
Number of lignites
W.R. Kaiser and E. Pew 1979

Figure 13. Occurrence of Deep-Basin Lignite in the Lower Part Part of the Wilcox Group in South Texas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N
Bryan
Madisonville
Lovelady
Lufkin
Huntington
BURLESON
LEE
BASTROP
WASHINGTON
AUSTIN
GRIMES
MONTGOMERY
WALKER
SAN JACINTO
TRINITY
POLK
TYLER
JASPER
WALLER
HARRIS
LIBERTY
HARDIN
FAYETTE
COLORADO
-1500 ft SSL base Yegua
EXPLANATION
Potential Lignite
Number of lignites
Abandoned mine
0
20 miles
0
32 kilometers
W R Kaiser and L C Johnson 1977

Figure 14. Occurrence of Deep-Basin Lignite in the Yegua Formation in East Texas (Kaiser [15])

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from earlier work [13], [14], [15]. Maps for the Wilcox and Jackson in south Texas were newly completed for this study (Figures 10 and 13). Mapping has shown deep-basin resources to occur primarily in the Wilcox Group and secondarily in the Jackson Group; deep lignite in the Yegua Formation is relatively unimportant at exploitable depths.

Major lignite occurrences in the Wilcox Group occur in the Calvert Bluff Formation in east-central Texas and in the upper two-thirds of the undivided Wilcox in east Texas. In south Texas lignite occurs in the lower part of the Wilcox just above the marine Midway Group, associated with the first Wilcox progradational sequence marking the initial Gulfward advance of the ancient Wilcox coastline. Jackson lignite in east Texas occurs in the middle Jackson Group, Manning and Wellborn Formations and their equivalents in the deep basin, and in south Texas in the lower part of the Jackson. Lignite previously assigned to the Yegua-Jackson in south Texas has been informally reassigned to the lower Jackson Group, a genetic package of strandplain/barrier-bar sands including some strata previously placed in the underlying Yegua Formation. This package is easily recognized throughout south Texas and means that all lignites can now be referred to one stratigraphic unit with a single depositional genesis. Yegua lignite in east Texas occurs in the middle two-thirds of the formation as small, highly discontinuous areas (Figure 14). On this basis the Yegua was eliminated from further consideration as an important host for in situ gasification.

9-1/8"

Estimation Methodology

Resource blocks were outlined by projecting mapped occurrences updip to the downdip limit of near-surface deposits or the 200 feet (61 m) depth line. Near-surface deposits have been recently outlined in a companion study using approximately 4500 density and lithologic logs. The minus 1,500 feet (450 m) SSL structure contour (approximately the 2,000 feet (610 m) depth line) on the base of the stratigraphic unit in question marked the downdip limit of the block. Other blocks are limited by the absence of lignite and are contained within the 200 and 2,000 feet (61 and 610 m) depth lines. Examples are blocks 3 and 4 on the Sabine Uplift Wilcox (Figure 15). Gaps between blocks generally coincide with major channel sand belts or inter-deltaic embayments in east-central and east Texas. The updip limit of south Texas lower Jackson lignite is defined along most of its extent by lagoonal sediments.

Tonnage factors were determined from an analysis of seam thickness in the adjacent near-surface deposit and from the distribution of seams greater that 5 feet thick in the deep basin. The average percentage of seams more than 5 feet thick at the near surface in a given borehole ranged from 21 to 31 percent for the Wilcox and 37 to 39 percent for the Jackson. The average number of near-surface lignites more than 5 feet thick in these two units ranged from 0.44 to 0.75 and 0.60 to 0.67, respectively. The number of deep-basin seams more than 5 feet thick rarely exceeds one. Analysis of these data show that the east-central and central Sabine Uplift Wilcox and Jackson have the thickest seams. The thinnest seams occur in the Wilcox northeast where among the Wilcox regions the number and percent of thin

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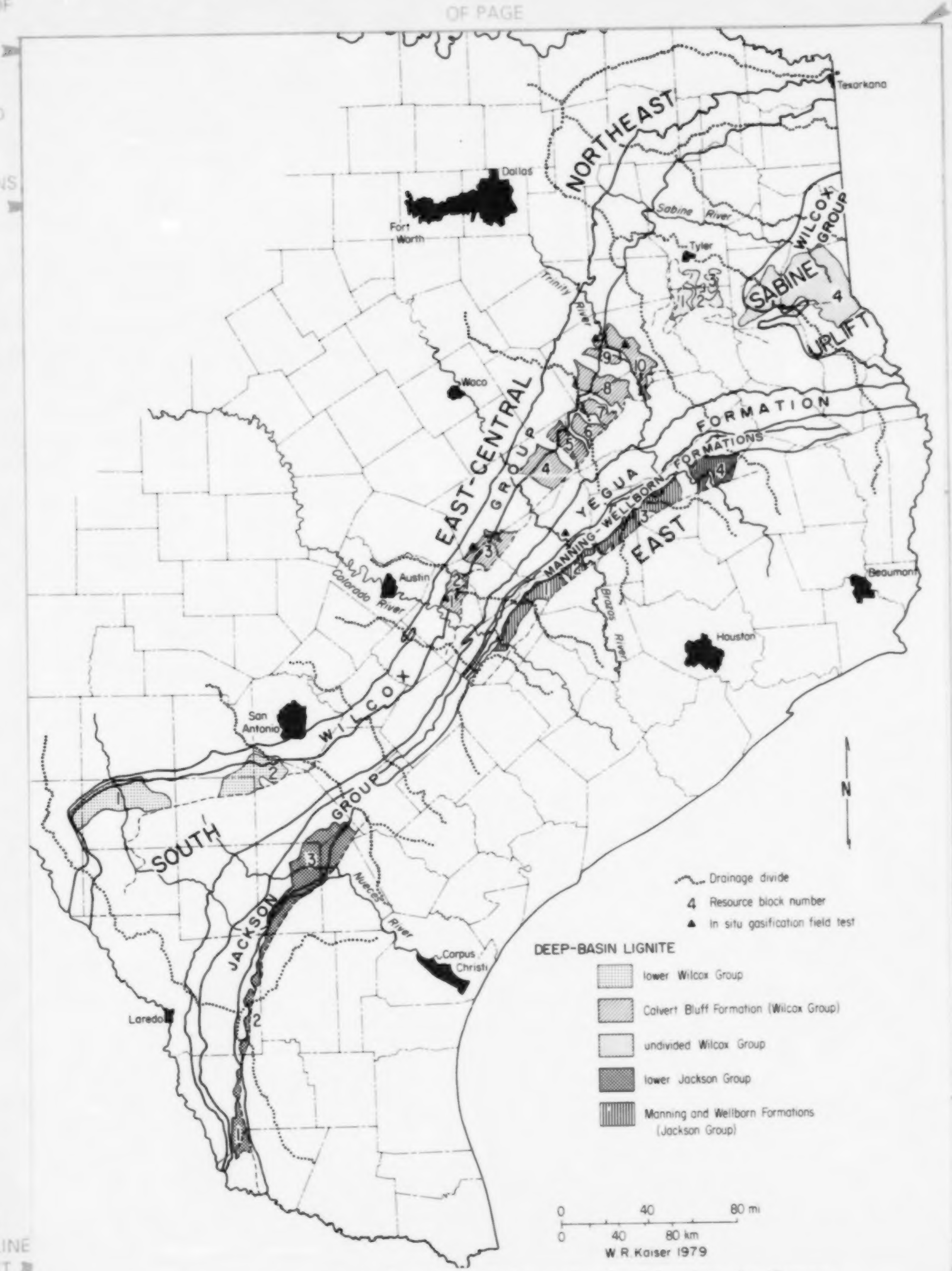
Texarkana
NORTHEAST
Dallas
Fort Worth
Sabine River
Tyler
WILCOX GROUP
SABINE
UPLIFT
Trinity River
Waco
EAST-CENTRAL
WILCOX GROUP
FORMATION
YEGUA
MANNING-WELLBORN FORMATIONS
EAST
Austin
Colorado River
Brazos River
Beaumont
Houston
San Antonio
WILCOX GROUP
SOUTH
JACKSON GROUP
Nueces River
Corpus Christi
Laredo
N
Drainage divide
4 Resource block number
▲ In situ gasification field test
DEEP-BASIN LIGNITE
lower Wilcox Group
Calvert Bluff Formation (Wilcox Group)
undivided Wilcox Group
lower Jackson Group
Manning and Wellborn Formations (Jackson Group)
0 40 80 mi
0 40 80 km
W.R. Kaiser 1979

Figure 15. Distribution of Deep-Basin Lignite in Texas

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seams is the highest (2.2 and 79 percent). Thick seams where present commonly are 5 feet thick or only slightly thicker. On this basis the Wilcox Northeast was eliminated from consideration as an important host for in situ gasification.

Tonnage factors assigned were 8,750, 13,125, and 17,500 tons per acre, equivalent to a 5-ft, 7.5-ft, and 10-ft seam, respectively. Factors were applied uniformly to each outlined resource block, corresponding to at least one 5-ft seam throughout, a 5-ft seam in one half and a 10-ft seam in the other half, or a 10-ft seam or two 5-ft seams throughout, respectively. The estimates are resources numbers with no consideration of any site specific factors such as hydrologic setting, roof condition, seam thickness, and depth of occurrence. Clearly, reserves or that lignite that can actually be economically gasified will be substantially less than the resource number.

GEOLOGICAL FACTORS IN GASIFICATION

Resources

Statewide resources are approximately 35,000 million tons divided 70 and 30 percent between the Wilcox and Jackson (Table 3). From a resource standpoint the Wilcox is clearly superior to the Jackson (24,000 vs. 11,000 million tons). The largest tonnages occur in the east-central and Sabine Uplift Wilcox and Jackson east (Table 4). These are most advantageously located with respect to potential markets such as the coastal petrochemical complex or existing lignite-fired power plants. Resource blocks in south Texas are geographically more isolated. The location of those blocks closest to San Antonio and Jackson block 3 immediately downdip of the San Miguel power plant may eventually make them economical (Figure 15). A 100 MWe unit using low-Btu gas (125 Btu/ft^3 or 4.66 MJ/m^3) would require about one million tons of lignite reserves per year, assuming a recovery of about 50% of the heating value of the coal.

Grade, Seam Thickness, Continuity

Coals of all grade have been successfully gasified in situ in the USSR, including brown coals with 30 percent moisture, up to 60 percent ash, and heating value as low as 3,500 Btu/lb (8.1 MJ/kg). Lignite is an ideal coal for gasification because of high reactivity at low temperature and shrinking behavior upon heating. The grade of Texas lignite (20 to 40 pct. moisture, 10 to 40 pct. ash, 0.5 to 2.5 pct. S, 4,300 to 7,700 Btu/lb as received (10.0 to 17.9 MJ/kg)) presents no special problems for gasification. However, there may be an optimum ash value of approximately 40 percent; it is believed that the higher ash value optimizes gasification, retains sulfur, and minimizes subsidence [16]. If this is true, then the Jackson lignite, particularly that in south Texas, may have an advantage.

Texas lignites are typically 2 to 10 feet (0.6 to 3 m) thick with thicker seams up to 15 feet (4.5 m) thick. Resource blocks of highest potential for thick seams or those in the 7 to 15 feet range are blocks 1,2,3, and 10 (Wilcox east-central), block 3 (Jackson east), block 4 (Wilcox Sabine

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TABLE 4. Deep-Basin Resources by Resource Block (millions of short tons)

Calvert Bluff Formation (Wilcox east-central)

*1.	823
*2.	672
*3.	2206
4.	1406
5.	862
*6.	857
7.	521
8.	1394
9.	325
*10.	1433
	10499

* subtotal 5991

Manning and Wellborn Formations (Jackson east)

1.	1462
2.	426
*3.	2570
4.	1142
	5600

Undivided Wilcox (Sabine Uplift)

1.	414
2.	610
3.	247
*4.	7543
	8814

Lower Jackson (south)

1.	829
2.	314
*3.	4132
	5275

Lower Wilcox (south)

1.	2783
2.	1848
	4631

*blocks of highest potential based on the criteria of the ideal gasifier, total starred resources - 19,836

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Uplift), and block 3 (Jackson south). Seams in the Wilcox are continuous for 2 to 15 miles (3.2 to 24 km) and display more lenticularity than those of the Jackson which are tabular and laterally continuous for up to 30 miles (48 km).

Differences in seam continuity and internal stratigraphy (presence or absence of splits) are correlated with ancient depositional environment. Wilcox lignite accumulated in interchannel basins where peat swamps were restricted to a maximum lateral extent of 15 to 20 miles (24 to 32 km) or the spacing of bounding alluvial ridges. In contrast, more laterally continuous lignites of the Jackson reflect accumulation in marshes on the lower delta plain or strandplain/lagoon complex. In these environments extensive blanket peats formed, extending across a variety of substrata such as filled distributary channel, beach sand, or bay and lagoon fill. Here lateral extent is ultimately controlled by the size of the underlying platform.

All seams contain splits. Predicting their presence or absence is virtually impossible; however, inferences about their relative abundance can be made. A peat (lignite) accumulating near a river levee or in a back-beach setting can be expected to have more splits than one distal to a levee or inland on a foundering delta lobe.

Thick seams are favored for gasification. Seams thinner than 6 feet (1.8 m) lose a larger fraction of their heat to the country rock (see Section 6), thus seam thickness is an important factor in the thermo-energy balance for gasification. Furthermore, linking at the bottom of a thin seam is not always certain. In linking, a split in the basal third of the seam may be advantageous helping to confine the backburn to the bottom of the seam. On the other hand, too many splits is a disadvantage, since concurrent gasification of a badly split seam is inefficient or even impossible [17]. Finally, minimum thickness for gasification may after all be dictated by completion technology, in which case 5 feet (1.5 m) is probably the absolute minimum.

Geohydrology

Gasification will be carried out in the freshwater column. Important factors for in situ gasification are host ground lithology, aquifer orientation, ground-water flow direction, and stream dissection. Ideally, the host ground for an in situ gasifier should be fine-grained low-permeability sediments in which a low-sand environment minimizes ground-water inflow, gas leakage, and pollutant migration (Figure 16). The gasifier should be roofed and floored by a thick mud or shale to minimize the threat of interconnecting through roof collapse overlying aquifers (sands) and the burn cavity. A mud roof may also improve gasification efficiency. Upon heating its volume may increase partially filling the burn cavity and minimizing the formation of bypass channels [17].

The Hoe Creek II field test, a three well test in semi- and unconsolidated sediments, had 70 feet (21 m) of roof collapse, communicating three major aquifers through a rubble column composed mainly of thermally altered roof material [18]. The worst possible geohydrologic setting is a thick

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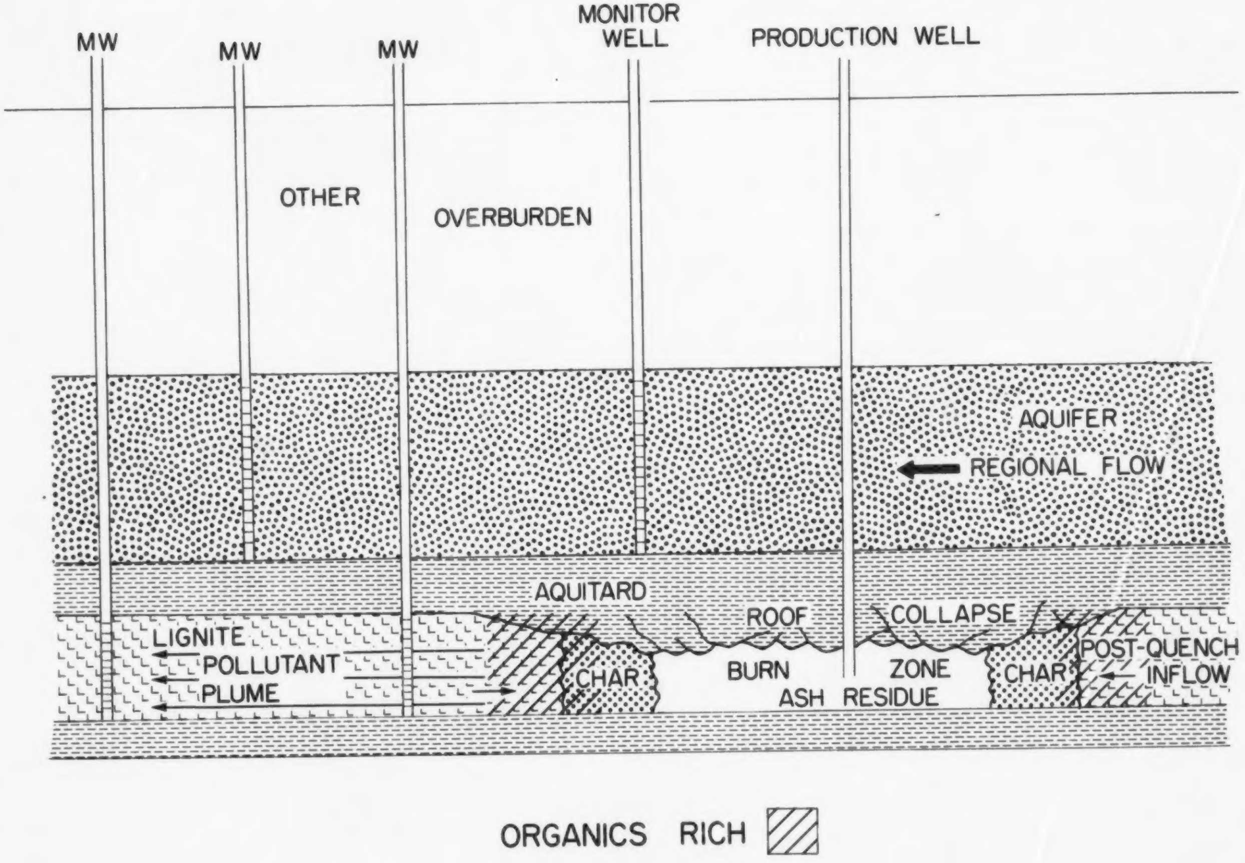
MW
MW
MW
MONITOR WELL
PRODUCTION WELL
OTHER
OVERBURDEN
AQUIFER
REGIONAL FLOW
AQUITARD
ROOF
COLLAPSE
LIGNITE
POLLUTANT
PLUME
CHAR
BURN
ZONE
ASH RESIDUE
CHAR
POST-QUENCH
INFLOW
ORGANICS RICH ▨

Figure 16. Post Burn In Situ Gasifier (Kaiser [23])

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sand resting directly above the seam to be gasified. Gasification in close proximity to water sands is essentially impossible [19].

The Wilcox is a far sandier geologic unit than the Jackson and is a major aquifer in Texas; only locally is the Jackson an aquifer. Overall sand percentage is much higher in the Wilcox than for any area mapped in the Jackson at comparable depths. Essentially, the Jackson is less transmissive or water productive and therefore hydrologically superior to the Wilcox.

Aquifers (sand bodies) in the Eocene of Texas have two basic orientations, approximately down the regional dip or perpendicular to it (compare Figures 5 and 9). In the Wilcox thick, areally-extensive, dip-oriented, fluvial channel sands of high hydraulic conductivity (6 to 20 m/d vs. 1 to 2 m/d or less in interchannel areas, about 0.45 m/d in lignite, and 10^{-4} m/d in muds) carry fresh water 2,000 to 3,000 feet (610 to 915 m) into the subsurface. In contrast, Jackson beach sands are strike oriented, limiting fresh-water recharge and mobility. Where these ancient fluvial or beach sands are oriented parallel to the ground-water flow direction, pollutant migration will be fastest; conversely, where normal to flow, migration will be slowed.

At the outcrop and in the shallow subcrop, flow in the Tertiary aquifers is strongly controlled by topography where uplift and erosion are advanced [20]. Flow to several hundred feet, perhaps to 1,000 feet (305 m), is topographically controlled and well within the depth range expected in early development of UCG. Major recharge and discharge areas are located along drainage divides and stream courses, respectively. This type of flow pattern has been documented for the Wilcox-Carrizo aquifer in the East Texas Basin by Fogg and Kreitler [21] (Figure 17). They have also shown from head differentials that flow in the confined or artesian portion of the system is downward from the overlying Queen City through the Reklaw aquitard into the Wilcox-Carrizo (Figure 4). In other words, a pattern of vertical recharge and discharge exists similar to that at the outcrop. The considerable vertical or cross flow means that the Wilcox-Carrizo aquifer is a rather leaky aquifer as are other Tertiary aquifers in Texas. Note that in Freestone and Anderson Counties flow is normal or oblique to the major channel sand belts (Figures 5 and 17). In Cherokee County flow parallels sand belts. Where uplift and erosion are less advanced, topography has less influence on flow direction. Indications are from head difference that ground water will flow from older to younger units under artesian conditions [20]. Where deeply buried, flow can be expected to move down regional dip (Figure 18).

In short, ground water may flow down, up, or oblique to regional dip from areas of higher energy potential (head) to areas of lower energy potential irrespective of geologic setting. However, hydraulic conductivity, transmissivity, and dispersion [22] are responsive to geologic setting.

In situ gasifiers are best located in recharge areas where flow lines diverge and attenuation is greatest. In addition, downward flow would tend to minimize the movement of pollutants upward into overlying intercommuni-

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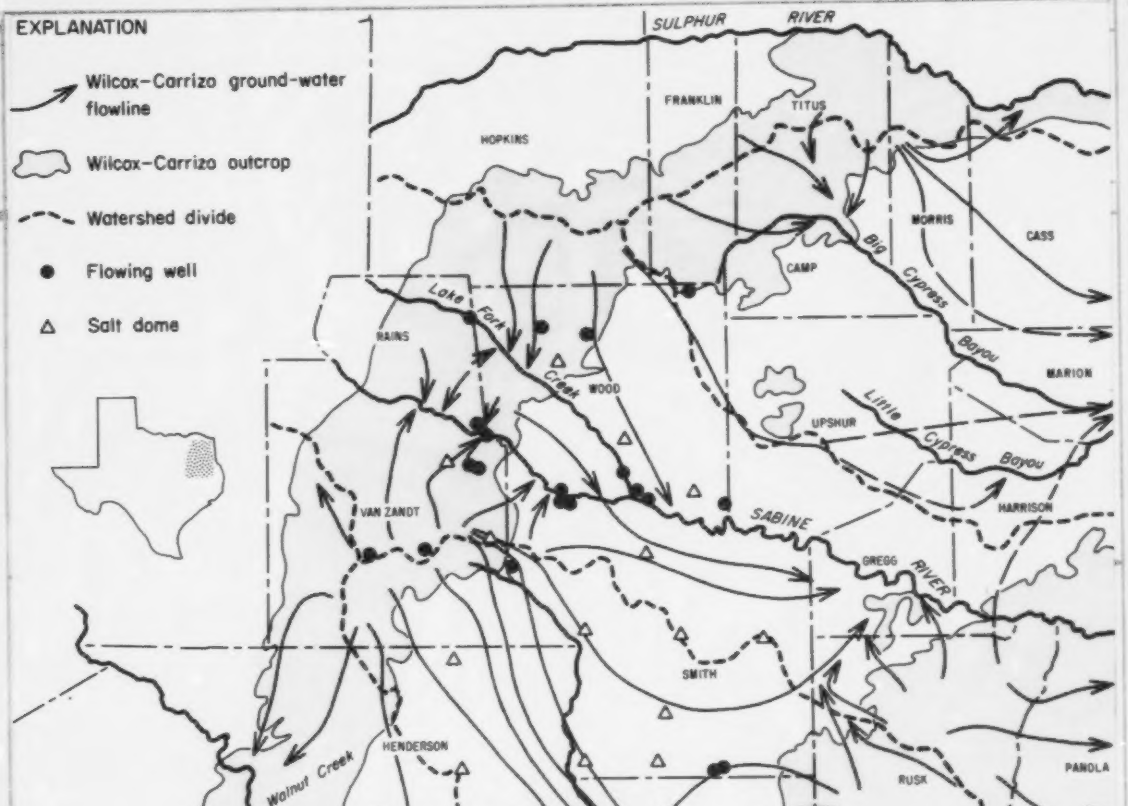
EXPLANATION
Wilcox-Carrizo ground-water flowline
Wilcox-Carrizo outcrop
Watershed divide
Flowing well
Salt dome
SULPHUR RIVER
FRANKLIN
TITUS
HOPKINS
MORRIS
CASS
CAMP
Big Cypress Bayou
RAINS
Lake Fork Creek
WOOD
MARION
UPSHUR
Little Cypress Bayou
HARRISON
VAN ZANDT
SABINE RIVER
GREGG
SMITH
HENDERSON
Walnut Creek
TRINITY RIVER
NAVARRO
RUSK
PANOLA
CHEROKEE
NECHES RIVER
ANDERSON
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Figure 17. Flow Lines in the Wilcox-Carrizo Aquifer in the East Texas Basin (Fogg and Kreitler [21])

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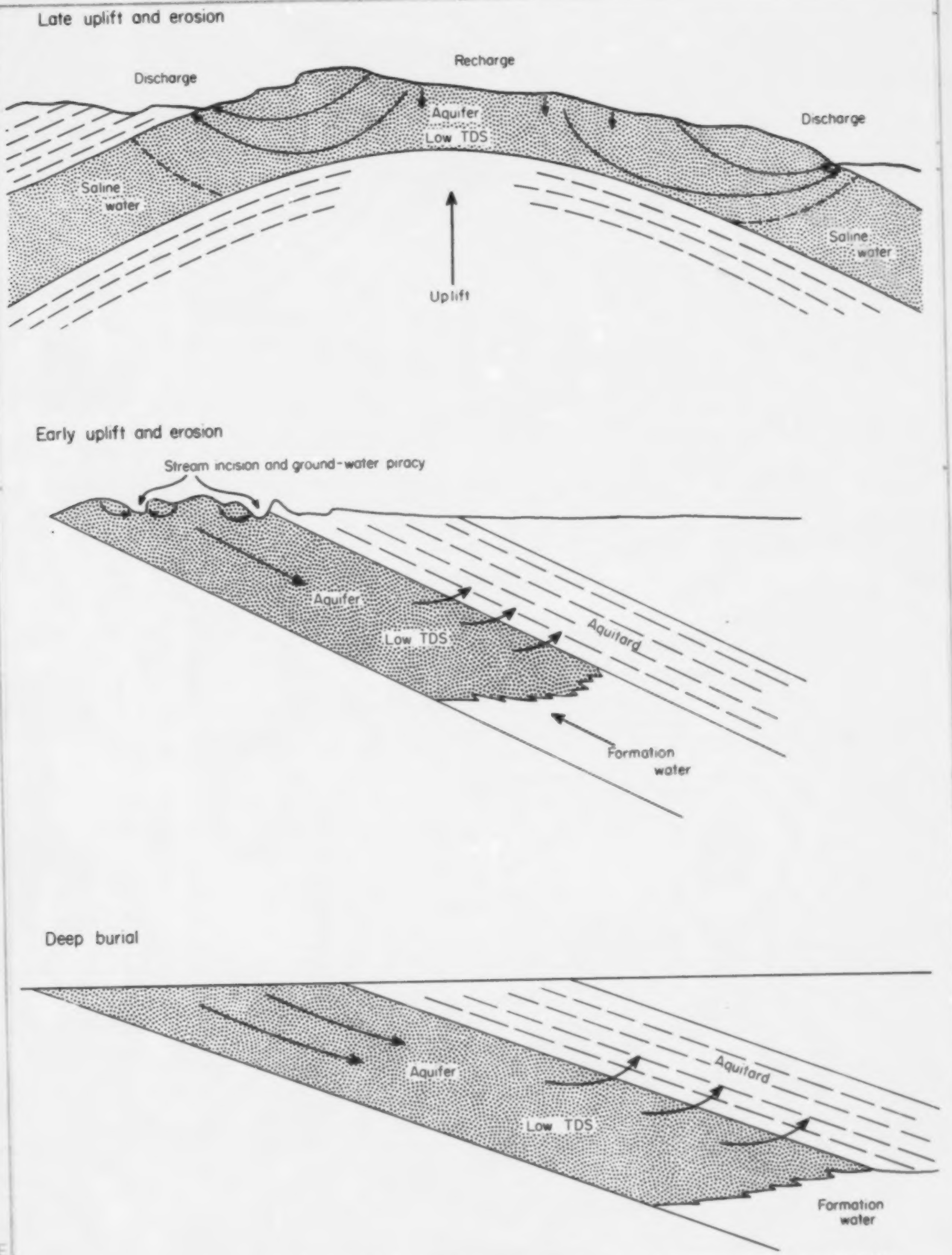
Late uplift and erosion
Discharge
Recharge
Aquifer
Low TDS
Discharge
Saline water
Saline water
Uplift
Early uplift and erosion
Stream incision and ground-water piracy
Aquifer
Low TDS
Aquitard
Formation water
Deep burial
Aquifer
Aquitard
Low TDS
Formation water

Figure 18. Stages of Aquifer Evolution (Modified from Kreitler [20])

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cated aquifers. Contamination of local water wells is a potential environmental threat. At discharge points flow lines converge, concentrating flow and making water inflow more of a problem. Here contamination of surface water is the threat. Ideally, resource blocks located in recharge areas are preferred sites for gasification, that is, those crossed by a drainage divide (Figure 15).

The largest field test in Texas has been conducted by Basic Resources (Texas Utilities Co.) 4.5 miles (7.2 Km) south of Tennessee Colony in Anderson County in an interchannel area of the Calvert Bluff Formation. A 7.5 foot (2.2 m) lignite was gasified at 270 feet (81 m) below the surface; it is separated from the Carrizo Sand, a major aquifer, by 75 feet (23 m) of muddy sediment. The site is between a recharge and discharge area. Flow is from the site toward the Trinity River roughly perpendicular to major channel sands in the Calvert Bluff (Figures 5 and 19).

Water Quality

In east Texas formation waters in the Wilcox and Jackson are well below 10,000 mg/l total dissolved solids. Generally, Jackson waters are of poorer quality than Wilcox waters. Only in the south Texas Jackson are waters found exceeding 10,000 mg/l TDS. The environmental impact of gasification in waters of that salinity is greatly reduced. More details on baseline water quality are given later in this section.

Structure

Structural factors play a role in in situ gasification. Perhaps dip is most important; it controls the gasification field design used. Dip may also influence pollutant generation and migration. In the gently dipping strata of Texas the linked-vertical-well technique is usually used. Gasification updip is preferred because of water and condensate collection. Steepness of dip controls the amount of resource available for recovery because drilling and casing costs are the most important economic variables. No resource blocks are deemed unacceptable because of dip.

Lignite is anisotropic; major cleat or fracture directions are usually present. Knowledge of the direction or maximum permeability is important in evaluating pollutant migration within lignite. There may be a relationship between cleat orientation and regional structural elements such that anisotropy could be predicted from lineament mapping. An understanding of the regional stress field may be a prerequisite to successful modeling of roof collapse [18]. A complexly faulted site should be avoided since faults provide additional avenues for pollutant migration. A potential problem area is block 3 (Jackson east) where many faults have cut the outcrop at the block's updip limit. Nevertheless, no serious problems are anticipated as long as gasification is carried out between faults and within individual fault blocks.

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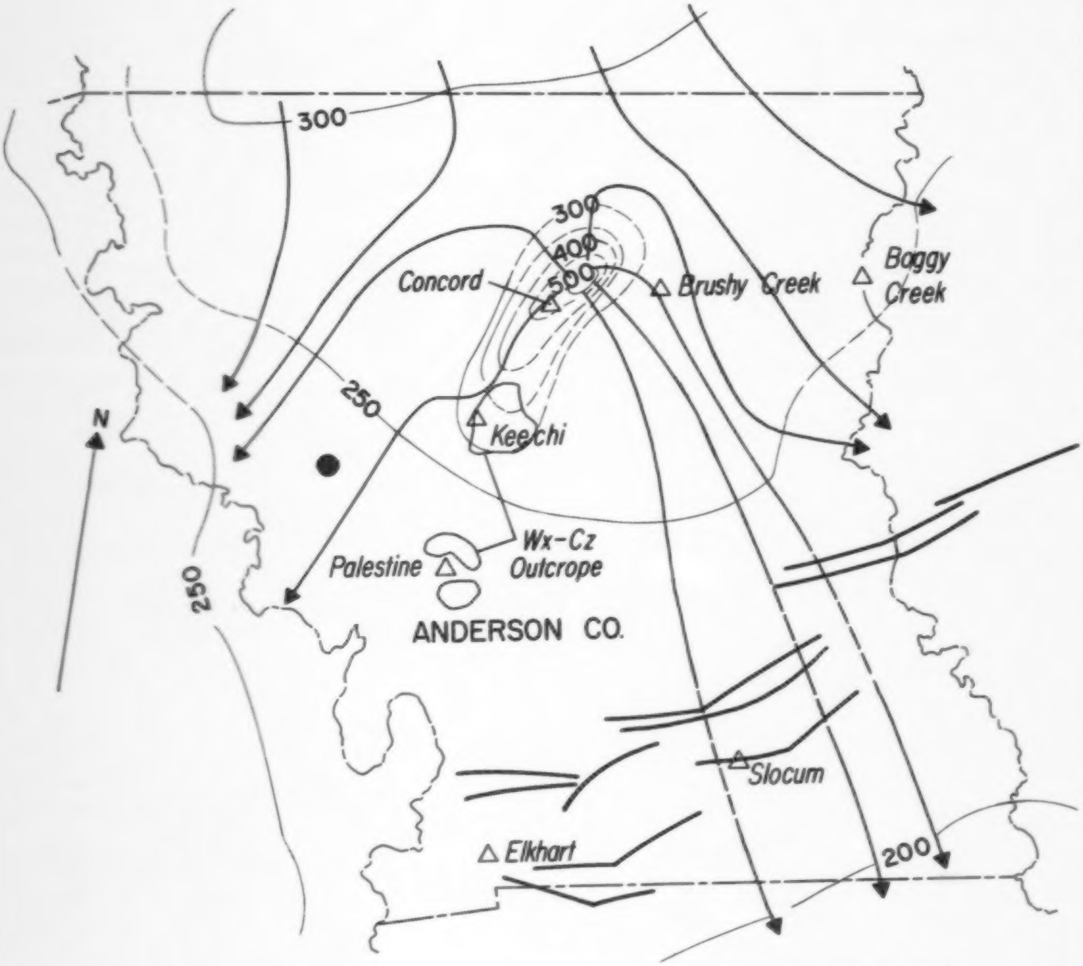
300
300
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Baggy Creek
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Slocum
Elkhart
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0 2 4 6 8 10 km

Figure 19. Potentiometric Surface of the Wilcox-Carrizo Aquifer, Anderson County, Texas, Basic Resources Tennessee Colony In Situ Gasifier at Solid Circle (Fogg and Kreitler [21])

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THE IDEAL GASIFIER

Criteria for selection of in situ gasifiers include geologic, hydrologic, and economic factors and are listed below in no preferential order:

(1) Resources in thick seams
(2) Continuous seams of uniform thickness with simple internal stratigraphy
(3) Proximity to markets
(4) Seams roofed and floored by thick mud
(5) Sand poor host ground (fine-grained low-permeability sediments)
(6) Proximity to a recharge area
(7) Aquifers oriented perpendicular to the ground-water flow direction
(8) Formation waters greater than 10,000 mg/l TDS
(9) Structural simplicity

Resources blocks of the highest potential satisfy several of these criteria. No block satisfies all the criteria. Jackson blocks meet more of them than Wilcox blocks, because more of the hydrologic criteria are met in the Jackson. Those starred in Table 4 (see Figure 15) are judged to have the highest probability for future commercial development. These areas should receive the highest priority for future research.

BASELINE WATER QUALITY ASSESSMENT

This section includes general water quality data from aquifers near important lignite deposits in Texas which are potential candidates for in situ gasification. Also, some sparse data are available from water samples taken directly from lignite seams.

Aquifers

Among the lignite-bearing geologic units only the Wilcox Group is a major aquifer; it is in intercommunication with the overlying Carrizo Sand, known collectively as the Wilcox-Carrizo aquifer. The Wilcox is 1,200 to 3,500 feet (355 to 1,067 m) of mainly unconsolidated sand, mud and lignite, whereas the Carrizo is 100 to 400 feet (30 to 122 m) of predominantly medium sand. The Jackson, the other important lignite-bearing unit, is approximately 1,000 feet (305 m) of mud, sand and lignite and is not an important aquifer. The upper Jackson Whitsett Formation is the most water productive part of the Jackson.

Wilcox wells yield from major sand units such as the Simsboro, large amounts (500 to 2,000 gpm) of fresh water (< 1,000 ppm). Smaller, finer grained sands yield moderate amounts (50 - 500 gpm) of fresh water. The Jackson yields mainly small (< 50 gpm) and, locally, moderate amounts of fresh to moderately saline water (3,000 - 10,000 ppm). Because permeability in unconsolidated sediments is largely a function of grain size and sorting, Wilcox permeabilities are greater that those of the Jackson. Hydraulic conductivities in the Wilcox Calvert Bluff are commonly 1 to 2 m/d and less than 1 m/d in the Jackson Manning. Simsboro and Carrizo conductivities are on the order of 6 to 20 m/d.

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Water Quality Data

The general water quality data used in this study were obtained from groundwater reports published by the Texas Department of Water Resources (see Bibliography). The counties involved and the aquifers are listed in Table 5. The following discussion of water quality includes the entire lignite-bearing aquifer in each county instead of only those parts where lignite is found. There are two reasons for this. First, there is no realistic way to determine from available reports where the well was actually completed (relative to the lignite seams). Secondly, studying the entire aquifer in the county will give an overall assessment of the water quality.

Total dissolved solids (TDS) was studied as related to well location from the outcrop area. Figures 20 and 21 are for the Wilcox and Yegua aquifers in two areas north of the Colorado River. The maps show that there is no correlation between TDS and well distance from the outcrop. TDS as a function of well depth was also evaluated. The results of this study were inconclusive; some counties showed a fairly good correlation (see Figure 22) while others showed none (Figure 23). The correlation, when present, indicates that TDS concentration increases with depth.

County average TDS values shown in Table 6 indicate that the Wilcox aquifer has the lowest overall average TDS concentration (512 mg/l); second is the Yegua (with 1,110 mg/l). Due to sparseness of data, an overall average for the Jackson is not included here. The trend of greater TDS with depth is not shown for Bastrop and Freestone Counties in the Wilcox. The reason for this reversal is due to several shallow wells having TDS greater than 3,000 mg/l. These analyses may not represent true formation water, due to the likelihood that contaminated surface water may have recharged these wells (Figure 24).

Figure 25 shows the results of the study of chloride concentration vs. well depth. The Wilcox aquifer (grouped with the Carrizo in Atascosa County) shows a slight decrease in chloride concentration as depth increases, and also shows an increase in very deep wells. An overall trend is unclear. Because of the variability of the data, chloride concentration vs. well depth was not studied further. Figure 26 shows the results of the study of the hardness in mg/l as $CaCO_3$ vs. well depth. This aquifer does show a drop in concentration in wells less than about 200 feet (61 m), but the exact trend thereafter is unclear. Hardness as $CaCO_3$ was thus not studied further.

Study of available water quality data has indicated that some correlation of water quality with region and depth is possible. The data support the conclusion that the Wilcox contains the best water quality. However, the data presented have documented enough variability in trends and parameters to preclude other general conclusions.

Water Quality in Lignite Deposits

The water quality within lignite seams is not available in published information. The major reason such data are not available is that lignites are not aquifers and are not used as a water supply. However, samples were

TABLE 5. Texas Counties Having Lignite Deposits

County	Aquifer	County	Aquifer
Anderson	Wilcox	McMullen	Jackson
Atascosa	Jackson; Wilcox	Madison	Yegua
Bastrop	Wilcox	Marion	Wilcox
Bowie	Wilcox	Milam	Wilcox
Brazos	Yegua; Jackson	Morris	Wilcox
Burleson	Yegua; Jackson	Panola	Wilcox
Camp	Wilcox	Rains	Wilcox
Falls	Wilcox	Robertson	Wilcox
Fayette	Jackson	San Augustine	Yegua
Franklin	Wilcox	Shelby	Wilcox
Freestone	Wilcox	Smith	Wilcox
Gregg	Wilcox	Starr Stet	Jackson
Grimes	Yegua; Jackson	Titus	Wilcox
Harrison	Wilcox	Trinity	Jackson; Yegua
Henderson	Wilcox	Van Zandt	Wilcox
Hopkins	Wilcox	Walker	Jackson
Houston	Yegua	Washington	Jackson
Lee	Wilcox	Wood	Wilcox
Leon	Wilcox	Zapata	Jackson
Limestone	Wilcox		

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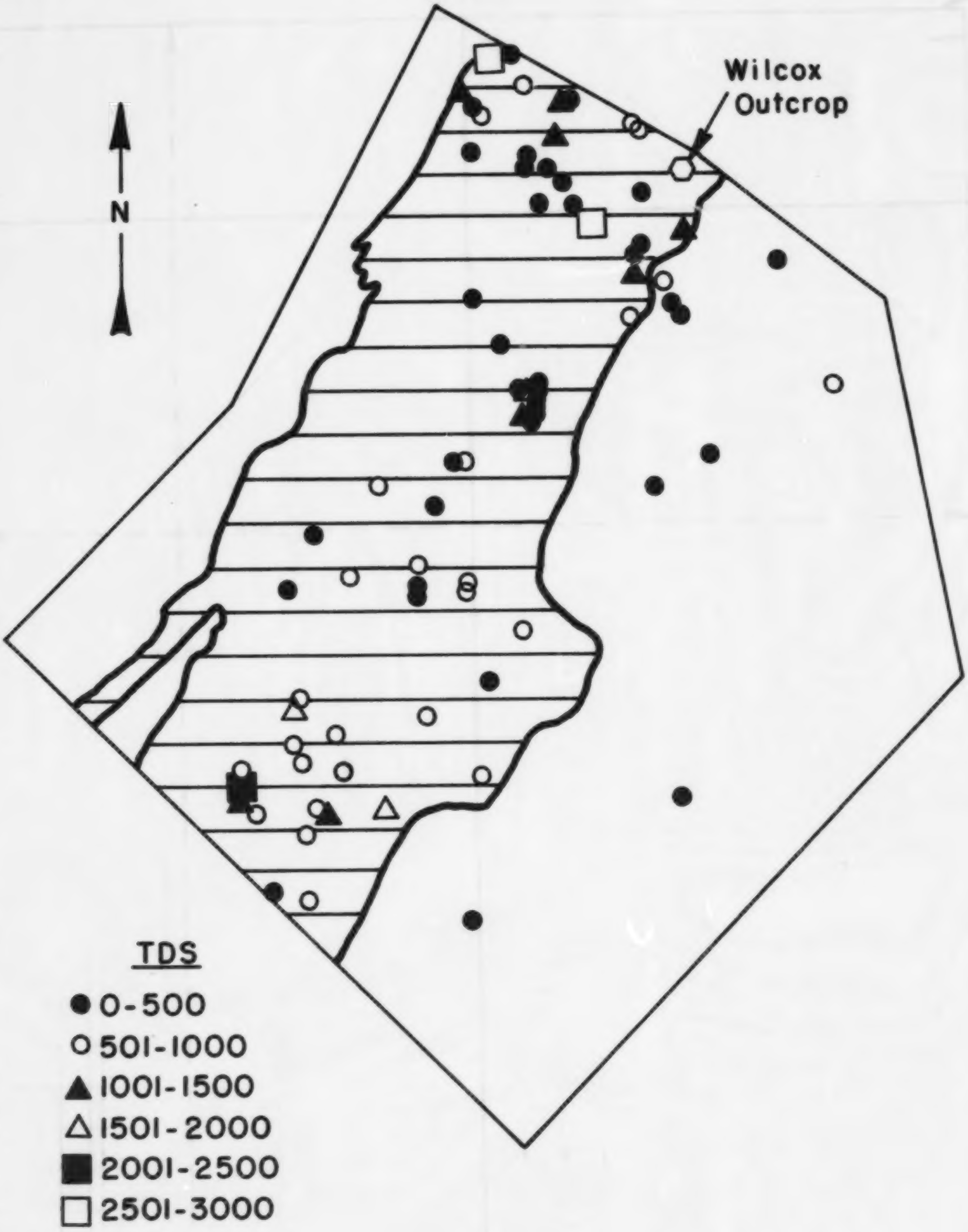
Wilcox Outcrop
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TDS
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■ 2001-2500
□ 2501-3000

Figure 20. TDS Map, Bastrop County, Wilcox Group

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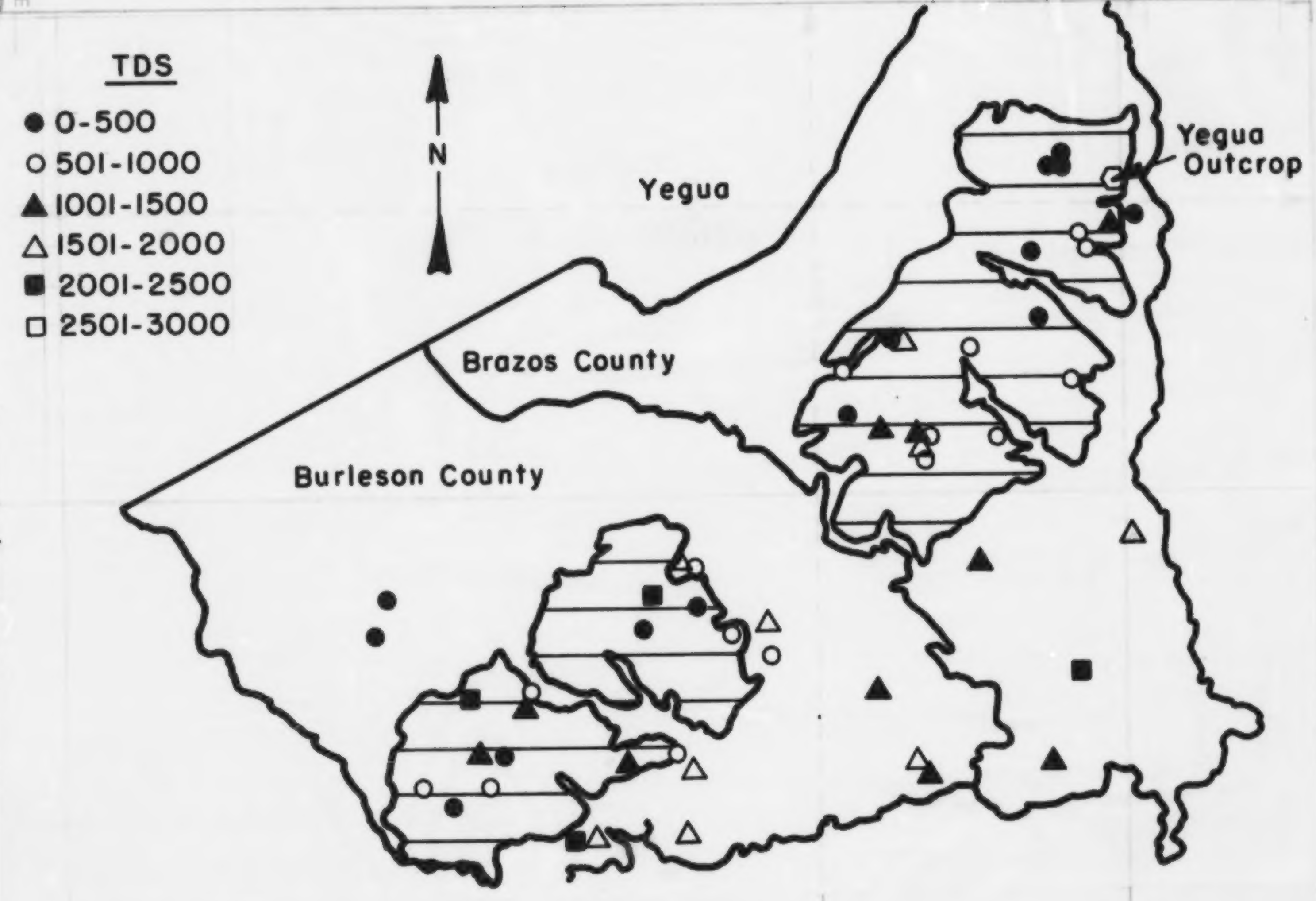
TDS
● 0-500
○ 501-1000
▲ 1001-1500
△ 1501-2000
■ 2001-2500
□ 2501-3000
N
Yegua
Yegua Outcrop
Brazos County
Burleson County

Figure 21. TDS Map, Yegua Formation

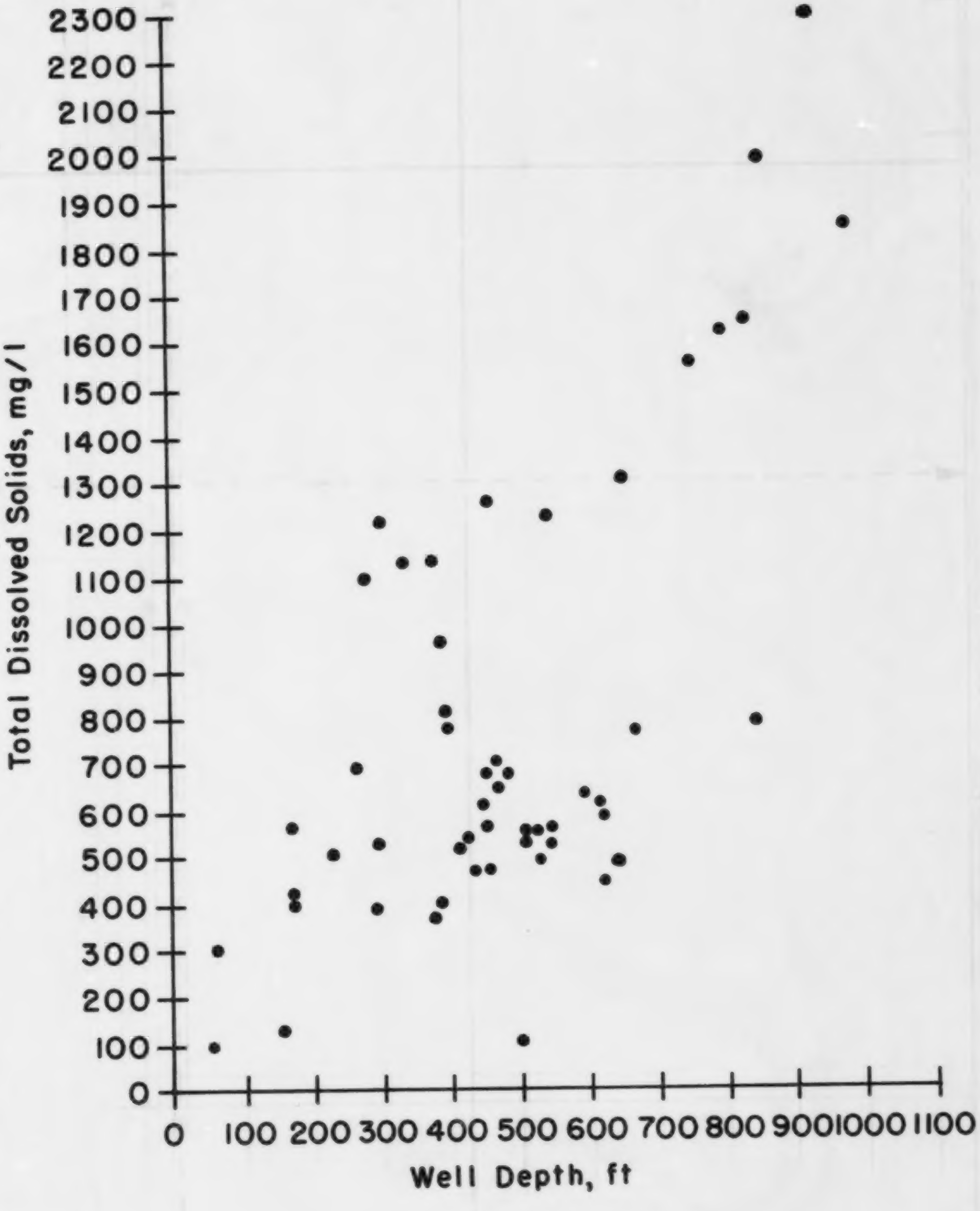

Figure 22. Gregg County, Wilcox Group, TDS vs. Well Depth

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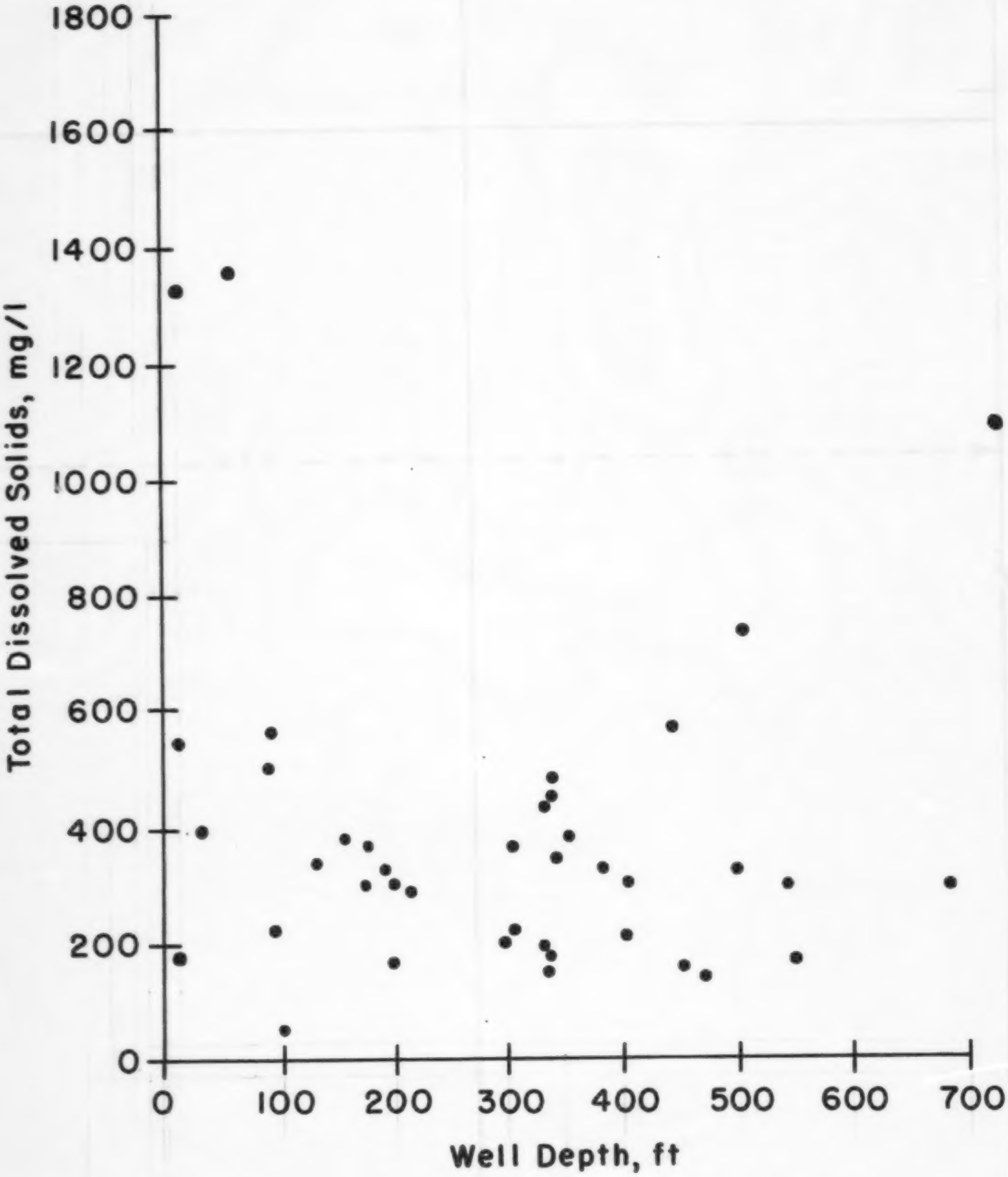

Figure 23. Van Zandt County, Wilcox Group, TDS vs. Well Depth

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TABLE 6. County Average TDS Values

Major Unit	County	Mean TDS, mg/l	Standard Deviation mg/l
Wilcox	Anderson	562	322
	Atascosa	488	526
	Bastrop		
	< 200 ft	796	691
	< 200 ft	598	268
	overall	681	498
	Freestone		
	< 200 ft	639	776
	< 200 ft	373	399
	overall	522	693
	Gregg	776	460
	Houston	440	165
	Rains	429	283
	Upshur	519	432
	Van Zandt	398	283
	Wood	308	229
	Overall Average	512	137
Yegua	Brazos	1123	791
	Burleson		
	< 200 ft	1122	956
	< 200 ft	1569	1038
	overall	1271	988
	Fayette	1370	1151
	Gonzales	1990	1227
	Grimes	1447	971
	Houston	616	380
	Sabine	588	355
	San Augustine		
	< 200 ft	414	580
	< 200 ft	709	1076
	overall	477	573
	Overall Average	1110	521
Jackson	Sabine	616	968

note: the standard deviation exceeds the mean in counties where the data scatter is great

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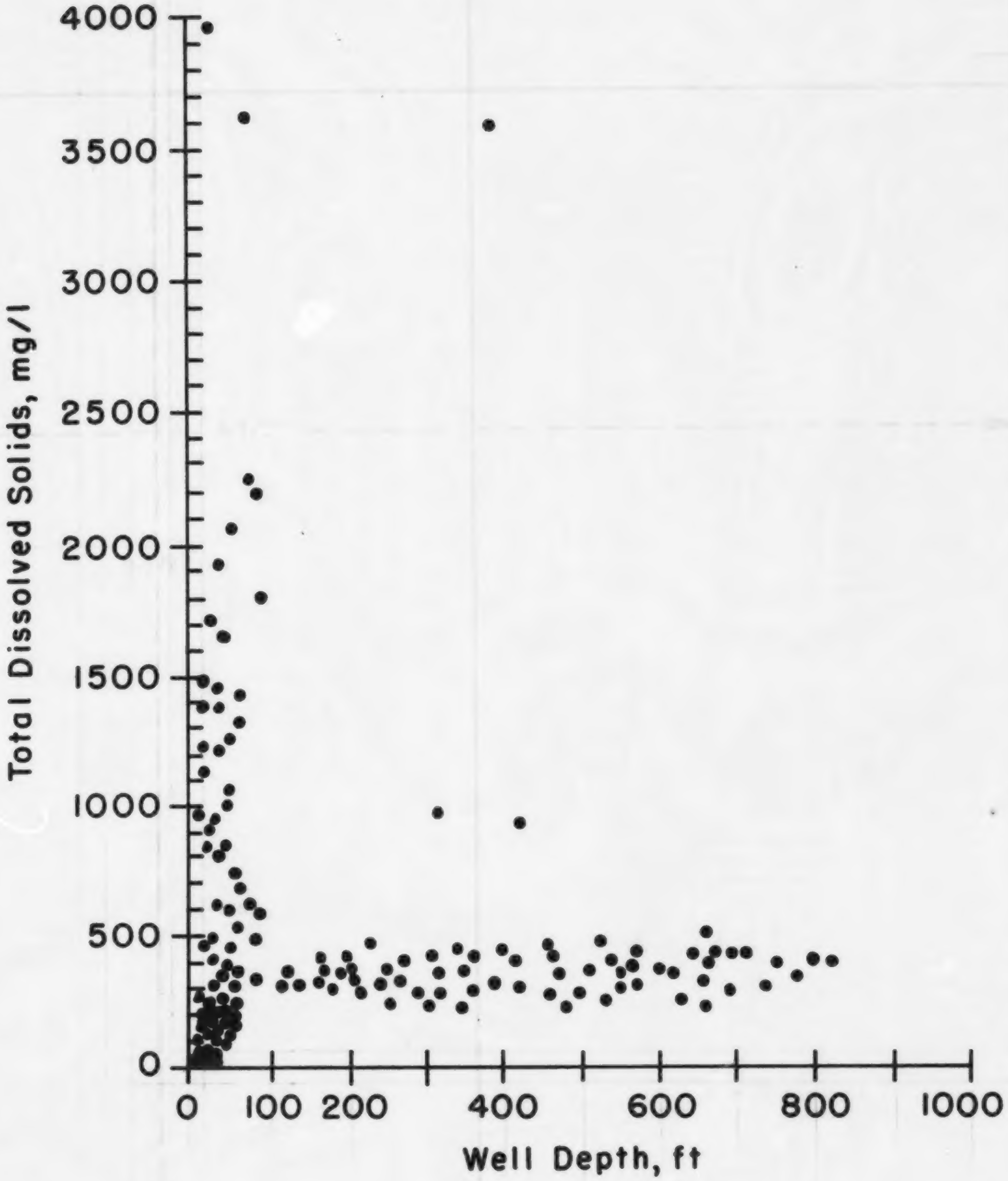

Figure 24. Freestone County, Wilcox Group, TDS vs. Well Depth

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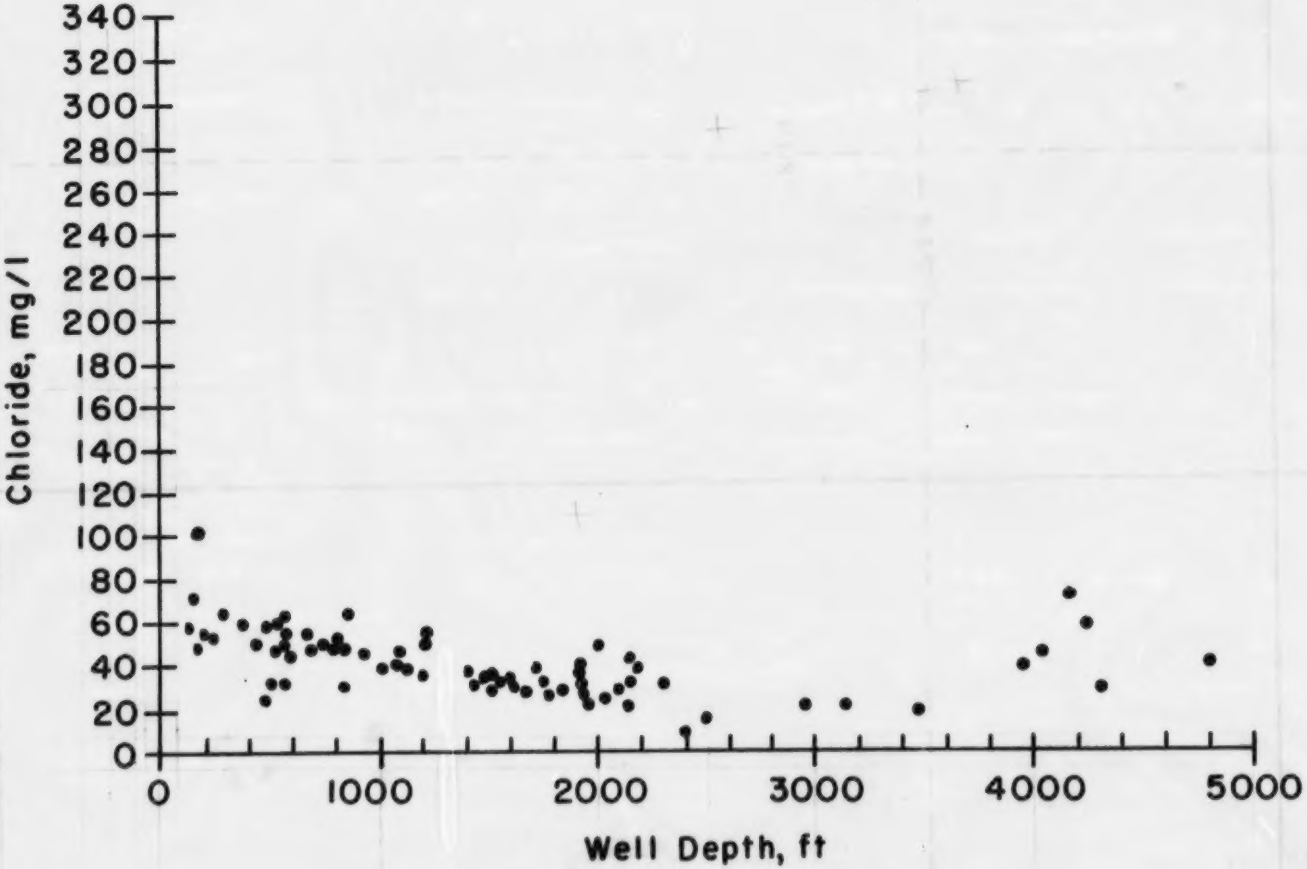

Figure 25. Atascosa County, Carrizo-Wilcox Aquifer, Chloride vs. Depth

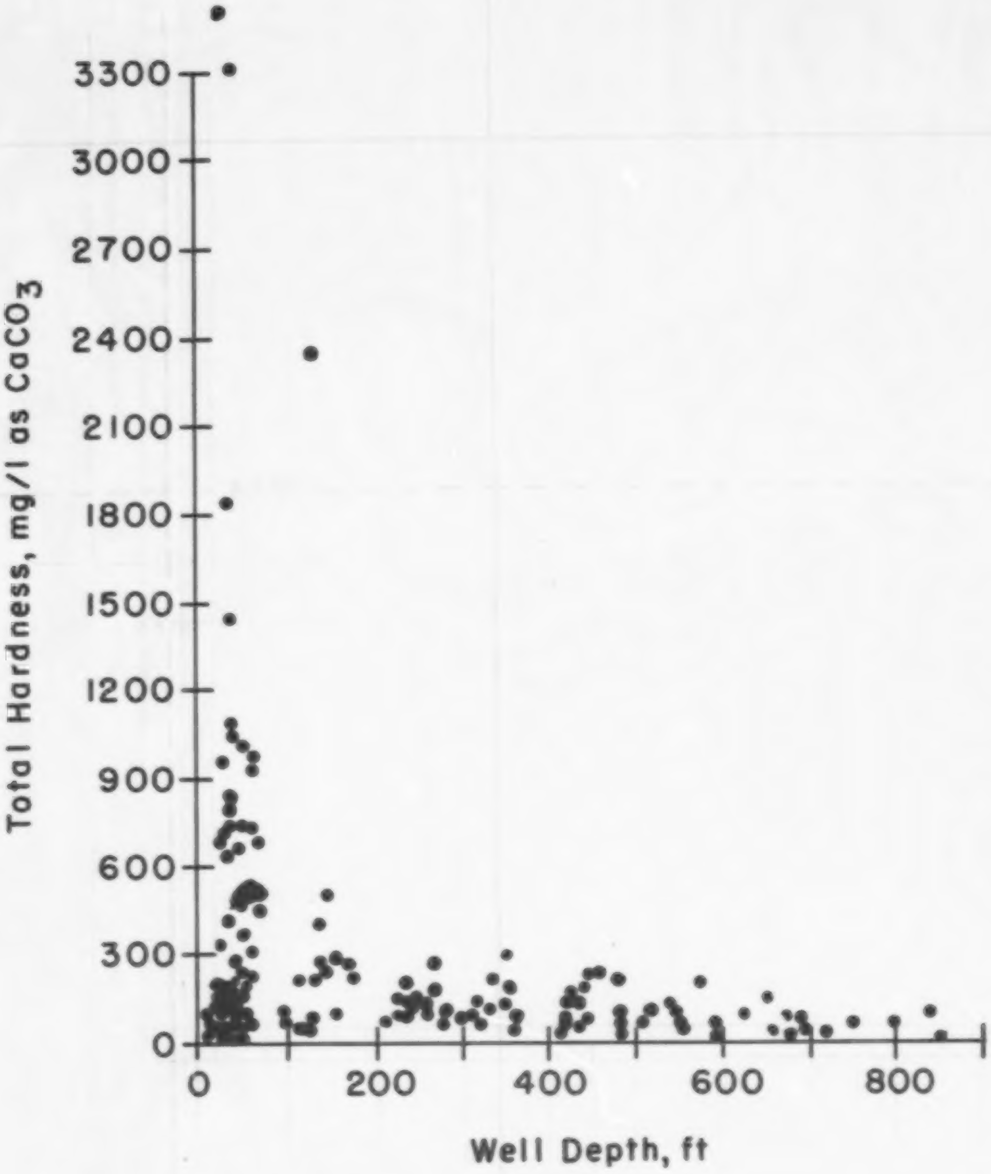

Figure 26. Freestone County, Wilcox Group, Hardness as CaCO$_3$ vs. Depth

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taken for a pregasification period at the Tennessee Colony site where Basic Resources, Inc. conducted in situ gasification tests in 1978. The data indicate the water quality is quite good (Table 7), particularly when it is compared to the data in Table 8 which shows the water quality in the overlying Carrizo aquifer, a major water supplier for the surrounding area. The difference in water quality is probably due to the adsorptive preference of the coal, especially for dissolved solids. Some species (such as TOC, sodium, and bicarbonate) are higher for the lignite seam.

FUTURE RESEARCH

Since in situ gasification will be carried out in the fresh-water column, there is a potential threat of groundwater pollution. A necessary first step to large-scale field testing and eventual pilot plants is the selection of gasification sites that minimize this threat. Depending on regulatory philosophy, active recharge areas may be preferred, where it is postulated that pollutants will be carried deep into the subsurface, providing maximum opportunity for natural dilution and attenuation.

Regional hydrochemical mapping (base of fresh water and water quality) and head mapping (potentiometric surface) in the Wilcox and Jackson Groups is proposed to help unravel regional hydrology. Water resistivity (Rw) can be used to indicate water quality and is obtained through resistivity or spontaneous potential (SP) measurements on electric logs (E-logs). Several thousand E-logs are available for analysis. Although calculated values of Rw are semiquantitative, the utilization of hundreds of logs allows delineation of meaningful patterns. Head data are available from the Texas Water Resources Data Bank, county reports of the Texas Department of Water Resources, and municipal well field records.

Areal extent of fresh water is reflected in the depth of its occurrence in an aquifer; a deep base-of-fresh-water indicates active basinward recharge whereas a shallow base indicated limited recharge. Basinward extending tongues of fresh water are revealed by Rw mapping. Abrupt decreases would indicate stagnation or discharge points. Areas of relatively inactive recharge are expected between tongues. Through analysis of head distribution loci of recharge and discharge can be identified. From good potentiometric surface mapping flow direction can be predicted. Without information on flow direction monitoring wells cannot be properly placed or hydraulic barriers established. Mapped patterns can be compared with lithofacies mapping to broadly characterize the relationship between hydrology and geology.

TABLE 7. Water Quality Within a Lignite Seam[*]

Component	Quantity[¢]	Component	Quantity[¢]
Sodium, mg/l	77.6	Ammonia-N, mg/l	0.69
Potassium, mg/l	3.0	Total Organic Carbon, mg/l	2.5
Calcium, mg/l	8.2	Arsenic, mg/l	< 0.01
Magnesium, mg/l	2.1	Aluminum, mg/l	< 0.1
Bicarbonate, mg/l	275	Cadmium, mg/l	< 0.01
Sulfate, mg/l	< 5	Chromium, mg/l	< 0.02
Chloride, mg/l	9	Copper, mg/l	< 0.01
Fluoride, mg/l	0.23	Iron, mg/l	0.86
Nitrate, mg/l	< 0.02	Manganese, mg/l	0.06
Total Dissolved Solids, mg/l	293	Mercury, mg/l	0.0026
Conductivity[#], M-mho/cm	488	Nickel, mg/l	< 0.02
Temperature[#], °C	23.5	Selenium, mg/l	< 0.01
pH[#]	8.3	Zinc, mg/l	1.8
		Molybdenum, mg/l	< 0.1

[*] Anderson County, Texas, seven to eight foot lignite seam, approximately 300 foot deep well.

[#] Field measurements

[¢] Arithmetic average of four samples

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TABLE 8. Water Quality in the Carrizo Aquifer[*]

Component	Quantity[c]	Component	Quantity[c]
Sodium, mg/l	44	Arsenic, mg/l	< 0.01
Potassium, mg/l	7.4	Aluminum, mg/l	< 0.01
Calcium, mg/l	84	Barium, mg/l	< 0.01
Magnesium, mg/l	31	Boron, mg/l	< 0.2
Bicarbonate, mg/l	35	Cadmium, mg/l	< 0.01
Sulfate, mg/l	367	Chromium, mg/l	< 0.02
Chloride, mg/l	66	Copper, mg/l	< 0.01
Fluoride, mg/l	0.1	Cyanides, mg/l	< 0.0006
Nitrate-N, mg/l	< 0.02	Iron, mg/l	25
Total Dissolved Solids, mg/l	701	Lead, mg/l	< 0.01
Conductivity[#], M-mho/cm	983	Manganese, mg/l	0.30
Temperature[#], °C	21	Mercury, mg/l	0.0028
pH[#]	6.4	Nickel, mg/l	< 0.02
Ammonia-N, mg/l	0.18	Selenium, mg/l	< 0.01
Total Organic Carbon	< 1	Zinc, mg/l	5.2
		Molybdenum, mg/l	< 0.1

[*] Anderson County Texas, Carrizo Sand aquifer above an in-situ lignite gasification operation. Samples taken from monitor wells.

[#] Field analyses

[c] Arithmetic average of six samples

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Section 6

ENGINEERING AND GEOLOGICAL FACTORS IN UNDERGROUND COAL GASIFICATION

Underground coal gasification is not a technology that will succeed at every site; candidate sites must be evaluated technically and economically prior to actual gasification. A number of factors which are conducive to application of UCG from a technical standpoint can be identified. In general it can be remarked that the Western U.S. coals appear to be the most suitable coals for application of UCG. Unfortunately, most Western coals, e.g., those in Wyoming, while very attractive from a technical viewpoint, are hampered by their location. The utilization of Wyoming coal will depend upon development of suitable schemes for production of petrochemicals such as ammonia or methanol. More efficient long distance transmission of electricity may also stimulate development.

Texas lignite, however, offers more flexibility in utilization schemes, as discussed in Section 4. A discussion of technical criteria for the successful utilization of a given coal seam by UCG is given below. These criteria can be grouped into three categories: those dealing with characteristics of the coal, those dealing with the overburden and other geological considerations, and those based on desirable operating conditions for the process.

COAL PROPERTIES

Most Western coals are shrinking coals in that they do not expand upon heating; this is extremely important in terms of maintaining a high flow rate at low pressures throughout the coal bed. For example, as these coals are heated, cracks open up and the structural integrity of the material is decreased, thus causing a large amount of reaction area to be exposed. Drying and devolatization causes the permeability of the coal matrix to increase markedly, often by a factor of 10^5 or more, thus enhancing its burning characteristics. On the other hand, most Eastern caking coals first expand (swell) upon heating, causing the internal pore structure to remain rather tight. In the presence of a confining pressure such as is experienced by coal at depth, crack formation due to gasification is restricted. The only recourse to this problem is directional drilling or repetitive reverse combustion steps, such as performed recently by Morgantown Energy Technology Center at a field test site in West Virginia.

It is also important that ignition be maintained in the system to achieve high sweep efficiency and that the coal be susceptible to gasification. Lower rank coals are more reactive, hence their gasification rates are higher at low

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temperature. Since water intrusion can lower reaction temperature, maintenance of ignition is crucial to obtaining a high resource recovery.

GEOLOGICAL FACTORS

Seam Thickness

Data from Russian operations indicate that the thermal efficiency of the process is significantly affected by the seam thickness variable, due to varying rates of heat loss to the overburden. Figure 27 (Gregg and Edgar [2]) shows the combined effects of seam thickness and water influx on the heating value of the gas produced. Note that the heating value tends to level off at about a 5-foot (1.5m) seam thickness; seams greater than 5 feet (1.5m) thick have rather similar heat transfer characteristics. Based on these data, a minimum seam thickness of 5 feet (1.5m) appears to be desirable for application of UCG. The maximum desirable seam thickness might be limited by the effects of large surface subsidence, which would cause excessive gas leakage and possible borehole damage. For Texas lignite the maximum thickness expected would be about 15 ft. (4.5m), which should not create severe rock mechanics problems. Seams over 100 ft. (30m) in thickness have been gasified (ARCO field test), although not completely.

Water Influx

Water influx, if abnormally high, can be extremely detrimental to the operation of the UCG system. In the extreme, the reaction can be extinguished. Usually a significant degradation in the overall thermal efficiency of the process results from water intrusion. We shall discuss this problem more quantitatively later in this Section. Figure 28 shows the typical relationship among thermal efficiency, water influx, and air injection rate [2]. In each case, there is an optimum water/air ratio; for water influxes larger than optimal, a large amount of energy is expended in vaporization and heating the water to the outlet gas temperature. The water entering the gasification zone can vary over time, and has a tendency to increase gradually rather than decrease, due to the enlargement of the cavity. For extremely wet seams, it may be that gasification with oxygen is warranted simply as a way of minimizing the water intrusion rate relative to the gasification rate. Use of oxygen rather than air will result in higher gasification rates, and it is expected that water influx rate will be independent of the gasifying medium. Positive control of water influx is desirable in any commercial UCG operation. Control of water influx by regulating the operating pressure has had mixed results in the field.

The water influx is also important from an environmental standpoint. In most underground systems, ground water flows into the cavity during gasification. Therefore the possible environmental impact of contacting this water with organic products from the gasification reaction must be considered. By operating the in situ gasifier at lower pressure than the hydrostatic pressure, moisture will seep into the gasifier, carrying with it organic materials from coal pyrolysis. In the gasifier, these organic materials are cracked to other hydrocarbons in the reaction zone and collected at the production well. The quantity of tars and oils collected during UCG tests is

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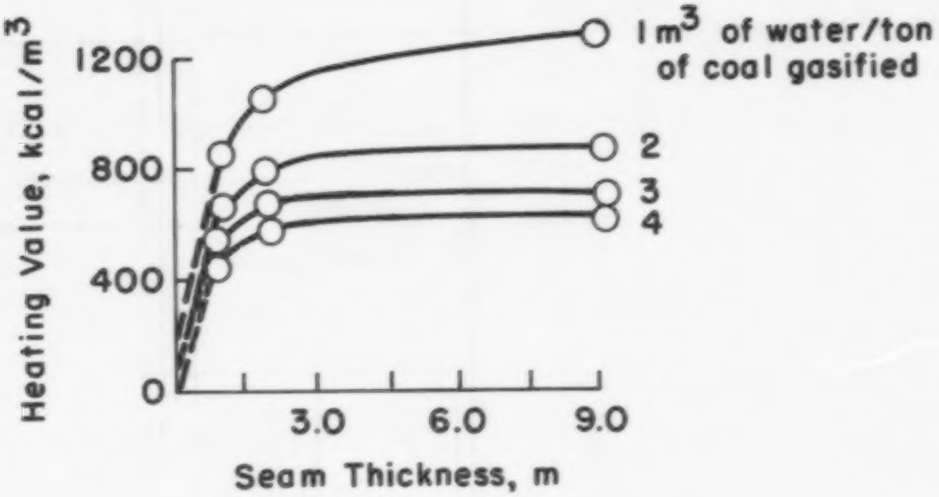

Figure 27. Effect on Seam Thickness and the Specific Water Inflow into Gasification Zones on the Calorific Value of Gas Obtained by Underground Gasification [2]

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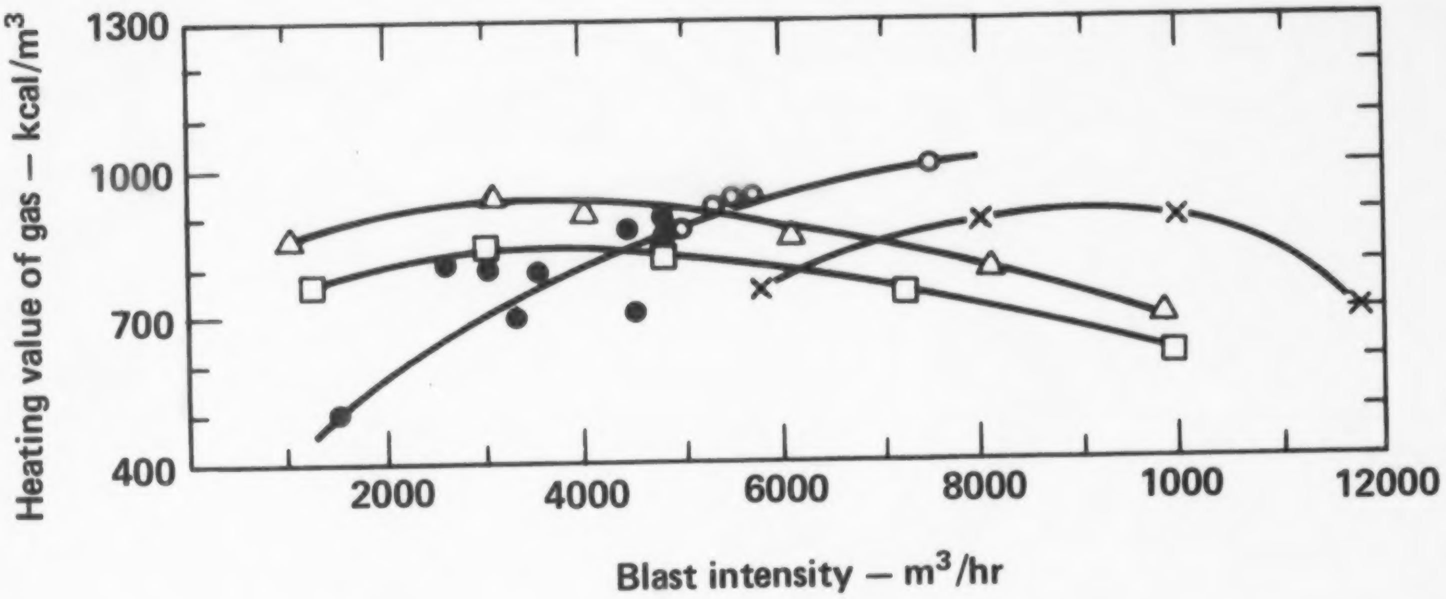

Key: 1—seam thickness of 14–16 m (Angren); 2—seam thickness of 5–6 m (Angren); 3—thickness of ~3 m (Yuzhno Abinsk).

Figure 28. Effect of Blast Intensity on the Heating Value of the Gas for Various Seam Thicknesses [2]

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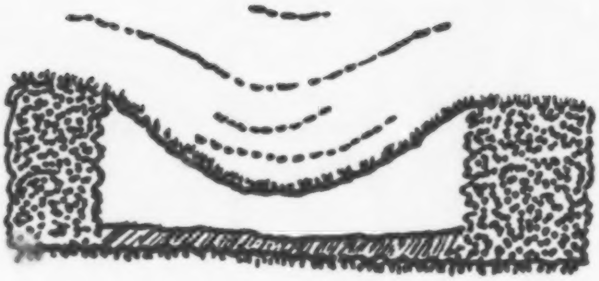

Figure 29. Character of the filling of the gasified space due to sagging of the roof rocks

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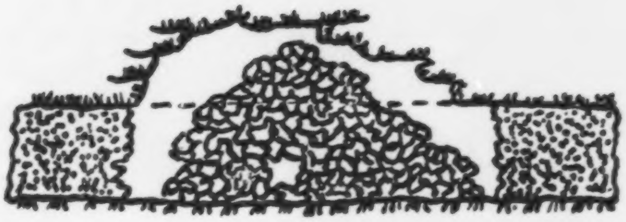

Figure 30. Character of the filling of the gasified space by the collapse of the roof rocks

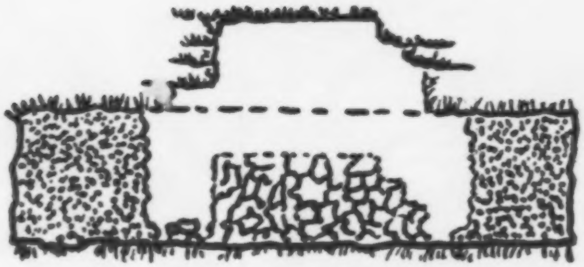

Figure 31. Scheme of the collapse of the roof rocks into the gasified space without considerable breakdown of these rocks

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lower than that from a Lurgi gasifier, indicating that decomposition of tars and oils does take place underground.

Roof Collapse

Roof collapse is at the same time beneficial and detrimental. As mentioned previously, increases in water influx and gas leakage can result from the collapse of the roof. On the other hand, roof collapse and minimum void space are desirable from the standpoint of having a thermally efficient operation. This is because the presence of void space underground encourages the undesirable phenomenon of oxygen bypassing, in which carbon monoxide is oxidized to carbon dioxide and gas heating values are decreased [25]. This results in a decrease in the heating value and a substantial increase in the outlet temperature of the gas, especially in thin seam gasification. The collapse of the roof can lead to the formation of channels by-passing the gasification area. In addition, communication can be established with highly permeable or water bearing strata, which can lead to considerably higher losses of blast and gas from the in situ generator, or to a higher influx of ground water. The roof in Texas is a mud/clay sediment with low mechanical strength. Therefore roof collapse to some degree is expected, although this does not necessarily mean that a noticeable amount of surface subsidence should occur.

According to Skafa [26] three types of changes in the state of the roof rock are distinguished:

The first type is represented by a sagging of the roof rocks without any substantial break in continuity. The gasified space is thus filled in, maintaining an approximately constant specific reaction surface of the coal in the gasification channel. This helps keep the characteristics of the blast and gas flow constant (Figure 29).

The second type is represented by collapse of the roof rocks with partial filling of the gasified space, due to the fragmentation of the roof rocks during their collapse. As a result, part of the gasified space is filled with rock rubble which diverts the gas flow. This effect may have a favorable effect on the course of the gasification process, as in the case of the sagging roof (Figure 30), since the fragmentation and bulking of the rock yields an effective increase in volume of this material.

The third type is represented by a collapse of the roof rocks in which the specific reaction surface of the coal in the gasification channel is not kept at an approximately constant value. This gives rise to bypass channels for the blast and the gas (Figure 31), when successively larger surface area of the overburden is exposed to the hot gas. This type of collapse is undesirable.

Surface subsidence is tied to roof collapse, although the relationship may be difficult to quantify. More discussion on subsidence effects is presented in Section 7.

OPERATING AND DESIGN VARIABLES

Product Gas Heating Value/Thermal Efficiency

The gas composition from UCG under ideal seam and operating conditions is comparable to that from moving bed surface gasifiers (such as Lurgi or Wellman-Galusha). However, precise control of geological or operating parameters is impossible to attain in normal applications. Variations in linkage paths, seam thickness, and water influx patterns are the chief factors causing departure from ideal conditions. The Hanna II field test was performed under nearly optimal circumstances in that a 30 foot (9m) thick seam was gasified, with the linkage path documented to be in the lower third of the seam. Water influx was also fairly low and a 60 foot (18m) well spacing was employed.

Over 38 days the heating value averaged 152 Btu/SCF (5.66 MJ/m^3, higher heating value). The UCG system was operated at relatively high flow and production rates compared to previous tests, which resulted in a very high cold gas thermal efficiency. The test was terminated before the combustion front reached the production well. A typical composition for the product gas is shown in Table 9, and for the purposes of comparison, the composition from a surface gas producer (Lurgi) operating on Western coal is also shown [16]. In comparing the two types of gasifiers, it should be pointed out that the UCG data represent an "optimistic" or best case.

TABLE 9

TYPICAL GAS YIELDS (WATER-FREE) FROM IN SITU AND CONVENTIONAL GASIFIERS

	UCG	Lurgi
Hydrogen	18.6	23.1
Methane	3.6	4.1
Nitrogen and argon	47.5	42.1
Carbon Monoxide	16.5	15.1
Carbon dioxide	13.1	15.1
Hydrogen sulfide	0.1	0.1
Ethane +	0.6	0.6
Higher heating value, Btu/SCF	161.0	175.0
MJ/m^3	6.00	6.52

It is also of interest to calculate the thermal efficiency of this UCG test facility and compare it with results from a Lurgi gasifier; these data are shown in Table 10 [16]. The thermal efficiency is defined as the heating value of the "cold" gas recovered divided by the heating value of the coal reacted plus energy added to the gasifier (e.g., steam). Energy used for air compression or seam preparation (linking) is not included in this comparison. It is clear that the in situ thermal efficiency (cold gas) can be higher than that for the Lurgi system (83% vs. 63%). One reason for this is that the Lurgi gasifier often uses excessive steam/air ratios (about 8:1)

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in order to prevent slagging of the ash. Also higher production of tars and oils are experienced in the Lurgi gasifier. Other advantages of the UCG system include the natural insulation provided by the overburden, which in this case yielded lower sensible heat losses than for the cooling system used in a conventional gasifier. The process heat from a gasifier jacket can be reused above ground, however. The fact that only a two-hole test system was used affected the reported efficiency for the Hanna test, since no significant gas leakage was experienced. Leakage problems will become more severe for a commercial-scale operation. It is interesting that later tests at the same site yielded lower efficiencies, mainly due to higher water intrusion and some differences in location of the linkage channel within the seam.

TABLE 10

COMPARISON OF HEAT BALANCES FOR IN SITU AND CONVENTIONAL GASIFIERS

In Situ			Conventional		
in	coal	100.0%	in	coal	96.2%
	(no air preheating or steam injection)			steam	3.7
				(air 250° F)	0.1
					100.0%
out	produced gas (cold)	82.9%	out	produced gas (dry, cold)	62.6%
	tars and oils	5.0		sensible heat (1200° F)	10.3
	sensible heat (512° F)	7.0		steam	1.9
	hot ash	2.1		bottom ash (combustion + sensible)	1.1
	heat loss to rock	3.0		dust, fines	3.2
		100.0%		tar and oils	12.9
				water jacket	3.4
				agitator cooling	1.5
				ambient losses	3.1
					100.0%

Heating values reported by personnel [27], [28] of Basic Resources, Inc., a subsidiary of Texas Utilities, for air and oxygen tests at Tennessee Colony (Figures 15 and 19) during 1978-79 are lower than those reported in Table 9. Table 11 shows gas composition and heating value for two periods of the air tests and one oxygen-blown period. The yields for air are probably not attractive, whereas the oxygen-blown product gas could be attractive if CO_2 were removed from the product gas. The CO_2 production was larger than would be expected; the possible reason for this could be heat losses to the overburden (a 7 1/2 foot (2.2m) seam was gasified), but more probably water influx from adjacent sands (aquifers) promoted the water gas shift reaction, converting CO to H_2 as well as lowering thermal efficiency. Figure 32 shows how the

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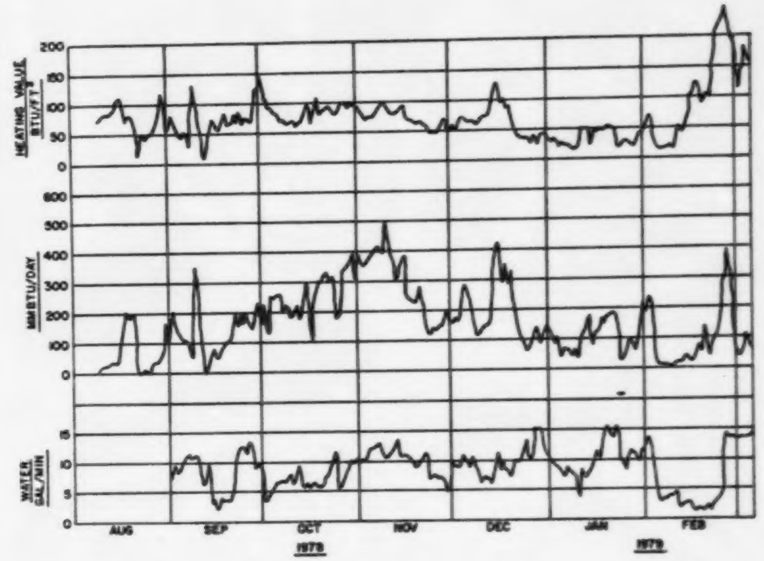

Figure 32. Air Injection Field Data from Tennessee Colony Test [27]

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gas production rate, heating value, and water influx varied over six months for air injection (10 wells), although the operating pressure was also changed during the same period.

No data on the energy balance for this test are available, although they can be surmised. The thermal efficiency for this test is in the range of 60-70%, rather than the 80+% result for Hanna II. Because of the large water intrusion rates Basic Resources has described this test as a "worst case" evaluation of UCG. There are other sites in Texas that could yield lower water influx rates, and a larger test would yield a lower effective ratio of water to oxygen. The Basic Resources test was a larger test than at Hanna in that two parallel paths and six successive rows (sets of injection and production wells) were gasified (75 to 100 ft or 23 to 30 m spacing). Other previous tests have used only a total of two wells (vs. 12 for this test). Personnel at Basic Resources have suggested that four or more parallel paths would reduce the effective water to air or oxygen ratio, thus enhancing heating values. Gas leakage for a larger test would be a factor (as high as 5% for a commercial operation), although Basic Resources has stated that gas leakage was negligible in their test.

TABLE 11

TYPICAL GAS COMPOSITIONS FOR BASIC RESOURCES AIR AND OXYGEN GASIFICATION TESTS [27], [28]

Gas	Air Injection (December, 1978)	Air Injection (January, 1979)	O_2 Injection well #12	O_2 Injection well #11
CO_2	17.6 %	19.4 %	50.7 %	46.0 %
CO	3.0	6.1	6.9	10.1
CH_4	2.5	3.5	7.6	7.0
H_2	14.2	13.6	33.2	35.7
N_2	61.1	56.2	0.4	0.3
H_2S	0.1	0.2	0.5	0.5
O_2	1.4	0.8	0.0	0.0
C_nH_n	0.1	0.2	0.8	0.4
Btu/SCF	82	103	223	237

typical outlet temperature = 400°F

The pertinent results on heating values at other test sites are summarized below:

(1) Texas A & M University [19] - Texas A & M has run two tests at different sites in Texas. The first site was near Bryan, Texas, Brazos

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County (Figure 15), utilizing a seam in the Yegua Formation with thickness between 2 and 4 ft. (.6 and 1.2m). A medium-grained sand lay directly above the lignite. Due to casing problems, there was extensive gas leakage (about 30%) into the sand; the thin seam made linkage difficult in addition to causing excessive heat losses to the overburden. This test was unsuccessful, with heating values below 100 Btu/SCF (3.7 MJ/m^3). A second test was performed near Alcoa, Texas (Figures 6 and 15) downdip of the ALCOA mine, on a 15 foot (4.5m) seam with desirable geological conditions. However, linkage problems also occurred in this test, ultimately causing low heating values and poor resource recovery. Attempts with shorter well spacings (e.g., 30 ft. or 9m) did not alter the results. The lack of success of this test compared to the Basic Resources test is not completely understood. Another test is planned for the Alcoa site in summer, 1980.

(2) Hoe Creek III [29] - Lawrence Livermore Laboratory performed a steam-oxygen burn which used directional drilling to produce the linkage path. The resulting heating values and gas composition for this test were similar to those in the third column of Table 11, due to fairly high water influx. The sub-bituminous coal gasified at Hoe Creek is also similar in proximate analysis to the Texas lignite used at Tennessee Colony.

(3) Atlantic Richfield (ARCO) - this test was performed in Wyoming on an extremely thick sub-bituminous coal seam - over 100 feet (30m) thick. The average heating values (200 Btu/SCF or 7.4 MJ/m^3) obtained were better than for Hanna II. Since the ARCO field test data is proprietary, the fraction of coal pyrolyzed and left in the ground (not gasified) is unknown. The resulting pyrolysis gas, which is rich in methane, ethane, and other higher hydrocarbons, enhances the heating value of fuel gas produced. Therefore misleading (optimistic) heating values can be obtained in field tests, although the more noticeable effects from pyrolysis usually appear early in the test [2], [30]. The heating values obtained at Hanna II are still the subject of controversy due to this question. ARCO has been evaluating a site in Bastrop County, Texas (Figure 15), for a possible future test.

(4) Gulf R & D [31] - Gulf operated a field test in conjunction with DOE late in 1979 on a steeply dipping coal seam near Rawlings, Wyoming. The field design for steeply dipping seams is similar to that for horizontal seams. The preliminary reports from the Gulf R & D test have been very promising, with heating values comparable to those from the ARCO test (greater than 170 Btu.SCF or 6.34 MJ/m^3).

In conclusion, the available test data seem to indicate that thick seams with low water influx yield satisfactory heating values for air injection (over 150 Btu/SCF or 4.90 MJ/m^3). However, thinner seams with higher water/air ratios, such as found in Texas lignite deposits, yield heating values which are closer to the 100 Btu/SCF (3.27 MJ/m^3) range. For this reason air injection does not appear to be very attractive for Texas lignite, except in the case where the gas is to be blended with solid fuel (see Section 4). Oxygen injection which should yield raw gas heating values over 200 Btu/SCF (7.4 MJ/m), appears to be favored at this time, especially given the multiplicity of uses for such a nitrogen-free gas. This gas could also be upgraded by removal of CO_2 prior to transportation or utilization. Superficially, the

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cost of energy per Btu should be lower for air injection than for oxygen injection, simply because of the cost of an oxygen plant. In addition, gas leakage is potentially more expensive because of the value of oxygen (vs. air). However, several possible advantages accrue to use of oxygen, in addition to having more options for utilization of the fuel gas:

(1) Water influx which may be excessive for air injection may be appropriate for oxygen injection, as discussed above.

(2) If the gas must be compressed and delivered at least 50 miles (80 km) away, the costs of compressing low Btu gas can become excessive (low Btu gas contains nearly 50 per cent N_2).

(3) Limited field evidence suggests that wider sweep efficiencies are attainable with oxygen vs. air. This offers the potential of wider well spacing and hence reduced drilling costs. This fact in itself may offset the cost of an oxygen plant.

The field test data for air injection presented earlier are comparable to heating values obtained in surface fixed bed gasifiers, such as Lurgi or Wellman-Galusha. However, the analogy between surface and underground gasifiers may not hold for oxygen injection. Stephens and Miller [32] have analyzed the Russian and Polish oxygen-steam and steam-enriched air in situ gasification experiments. The heating values reported varied from 220 to 270 Btu/SCF (8.2 to 10.0 MJ/m^3), with the following gas composition ranges: CH_4, 2-6%; H_2, 37-42%; CO, 18-27%; CO_2, 25-34%. Note the low methane per cent, due to the low pressure of operation. The CO_2 figure is quite high, and is indicative of the fact that these experiments consumed much more oxygen per unit weight of coal than for Lurgi gasification. Comparison of the product yields with thermodynamic calculations suggests that some bypassing of oxidants and secondary oxidation of product gases may be occurring, or excessive water intrusion may be reducing the thermal efficiency. Specific conclusions cannot be reached given available data.

One way to illustrate the effects of water influx and heat losses on the product gas composition and heating value is by computer simulation. Using a computer code developed at the University of Texas [33], the effects of water influx and heat losses on gas composition can be predicted for Texas lignite, as shown in Tables 12 and 13. These data illustrate the strong influence water influx has on gas composition and suggest that methods to reduce water influx should be considered seriously as a means to enhance thermal efficiency. The similarity between the simulated results and those in Table 3 at a water influx ratio of 5 to 6 is notable, lending some credibility to the model predictions.

Production Pressure

The production pressure desirable for UCG is a fuzzy issue because it is so site-specific. First of all, there are empirical trade-offs that will occur among gas leakage, water influx, and production pressure. It would be desirable to operate at slightly below the pressure corresponding to the hydraulic head for a given depth, since at this pressure the encroaching water would seal the gasifier and help reduce gas losses. Higher pressures would exacerbate the leakage of gas and are apparently not feasible. On the other hand, gasification yields (especially methane) are improved at higher

TABLE 12

PREDICTED GAS COMPOSITION FOR OXYGEN INJECTION WITH VARIABLE WATER INFLUX
(Representative Texas lignite; environmental heat losses = 9%)

Water influx mole / Oxygen mole	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Product gas comp.											
Nitrogen	-	-	-	-	-	-	-	-	-	-	-
Hydrogen	26.0	30.4	33.4	35.6	37.0	37.8	38.1	37.8	36.7	34.5	30.7
Carbon Monoxide	55.0	44.8	37.0	31.0	26.1	22.0	18.6	15.6	13.0	10.7	8.6
Carbon Dioxide	11.8	18.0	23.1	27.1	30.7	34.0	37.2	40.5	44.1	48.4	54.0
Methane	6.1	5.8	5.6	5.4	5.3	5.2	5.2	5.2	5.2	5.4	5.7
Moisture Content mol/mol input O_2	0.06	0.28	0.59	0.98	1.4	2.0	2.55	3.2	3.9	4.6	5.4
Lower Heating Value Btu/SCF	340.	312.	292.	276.	262.	250.	238.	227.	216.	204.	190.

TABLE 13

PREDICTED GAS COMPOSITION FOR AIR INJECTION WITH VARIABLE WATER INFLUX

(Representative Texas lignite; environmental heat losses = 9%)

Water Influx / Oxygen (mole / mole)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Product Gas Comp.											
Nitrogen	44.0	43.2	42.9	43.2	43.8	44.9	46.5	48.5	51.1	54.4	58.7
Hydrogen	14.6	17.3	19.1	20.3	20.8	20.9	20.5	19.6	18.1	16.0	13.1
Carbon Monoxide	31.0	25.7	21.4	17.9	14.9	12.4	10.2	8.2	6.5	5.0	3.7
Carbon Dioxide	6.4	10.0	12.9	15.1	17.0	18.5	19.6	20.6	21.2	21.6	21.8
Methane	3.4	3.3	3.1	3.0	2.9	2.8	2.7	2.6	2.5	2.4	2.3
Moisture Content mol/mol input O_2	0.05	0.26	0.57	0.96	1.4	1.9	2.5	3.1	3.8	4.5	5.3
Lower Heating Value Btu/SCF	190.	179.	167.	157.5	148.	138.	128.	118.	106.	94.1	79.7

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pressure, and it is more economical to compress injection gases than product gases, because of the increase in volume which occurs during gasification. Therefore if the gas is to be transported over any distance, compression of the injected gases to as high a level as possible is desirable. There has yet been any field demonstration that UCG can be operated at high pressure (e.g., 20 atm or 2.03 mPa, such as in surface gasifiers). Therefore, virtually all methane that is produced in field tests is due to coal pyrolysis.

Well Spacing

The typical injection-production hole spacing used in U.S. and U.S.S.R. field tests is 60 to 100 feet (19 to 30m). It is desirable to maximize well spacing since, for thin seams, the gas cost is sensitive to drilling costs and the number of holes drilled; these costs decrease with wider spacing. The main constraint to longer spacing is the distance over which linkage can be successfully performed. Lateral spacing could be chosen to minimize subsidence, although subsidence has not been found to be a major difficulty in field tests. The subsidence question is discussed below in more detail.

Sweep Efficiency

Historically, sweep efficiencies during UCG have varied from 10% to nearly 90% (sweep efficiency is defined as the coal contacted or reacted over a specified area of operation). The Russians appear to have achieved satisfactory contacting of the coal (about 70 to 80%) and they apparently did not leave any coal underground deliberately. The field design must predict the recovery per hole drilled, i.e., the region of influence for a given set of injection and production holes. A maximum sweep efficiency should correspond to a minimum cost operation. Russian experiments indicated that borehole spacing affected sweep efficiency. For example, for 25 meter spacing, a coal recovery of 83 per cent resulted, while for a 40 meter spacing the fractional recovery dropped to 63 per cent. It is interesting to note, however, that experiments with oxygen enrichment gave higher sweep efficiencies than those obtainable with air injection [7]. This indicates that the extra capital and operating costs incurred by an oxygen plant may be offset by higher sweep efficiencies and higher product gas heating values (but not higher thermal efficiencies).

Because of the limited amount of field data available, engineering judgment must be used in developing the key design assumptions for sweep efficiency, which are necessarily subjective. There are two extreme cases that can be considered for setting lateral well spacing:

(1) locate the parallel gasification paths on an approximately square spacing (equal to borehole spacing from injection hole to production hole). The goal of this configuration is to maximize coal recovery and not leave pillars separating adjacent gasification channels. While 100% coal recovery is not practically realizable, over 80% sweep efficiency could be obtained based on previous field test experience. Apparently the Russian UCG experiments used both lateral and axial linkage paths to assure a broad sweep and

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maximum resource recovery. Surface subsidence is not prevented, although for deep, thin seams, long term surface deflections may be quite small. Roof collapse, on the other hand, should be interpreted as a question separate from surface subsidence, since massive roof collapse involved with thick seam gasification may not cause a corresponding amount of surface movement. The Hoe Creek II test by Lawrence Livermore Laboratory is a case in point, since there was roof collapse extending 70 ft. upwards from the seam but no significant surface disturbance. On the other hand, the more recent Hoe Creek III test did develop a subsidence bowl of 3m wide x 13.5m long x 3 m deep due to roof collapse. Roof collapse is undesirable because it generally causes increased water influx and gas leakage, and it is generally unavoidable in the traditional linked vertical well approach.

(2) Select a spacing with pillar widths to prevent or minimize surface subsidence. Use of this type of field design is somewhat more costly, since larger coal deposits (areal extent) are required. However, the produced gas cost is not very sensitive to leaving pillars underground, since coal "in the ground" is not too valuable, except for the initial leasing cost. Surface subsidence for UCG is largely unpredictable given current technology, hence conservative pillar design is a reasonable assumption. The presence of pillars may reduct water influx and gas leakage and may help prevent contamination of overlying aquifers due to reduced strata movement. Another advantage of leaving pillars underground is that they may be largely pyrolyzed, enhancing the normal gasification products with additional volatile hydrocarbons. In some field tests on Wyoming coals material balance calculations have shown that as much as 40% of the energy produced may be due to carbonization; the carbonization sweep or char zone could be nearly twice as large as the gasification zone [30]). The required pillar size and hence lateral well spacing is difficult to predict since an ultimate maximum channel size must be predicted, and the channel may not be uniform in size over the production path.

Based on reported data from the Russian field work on lignite gasification [34], a linear relationship appears to exist between the percentage of coal remaining in the ground and the distance separating the production well from the associated injection well (Figure 33). While the source is not specific in defining percentage losses of coal, it is assumed that these losses are more a function of uncontacted coal than thermal efficiency. Likewise, it is assumed that these losses should be interpreted on the basis of square spacing, such that if the distance between the injector and producer were set at 100 feet (30m), the percentage losses of coal would be 23% (from Figure 33), hence 77% of the coal within a 100 ft x 100 ft. (30 x 30m) grid, is removed by the combustion process. Figure 33 illustrates the need to optimize well spacing, since wider well spacing requires relatively lower drilling costs but results in a lower coal recovery.

A 77% recovery for 100 feet (30m) square spacing implies that the average channel width would be 77 feet (23m). Of course the actual channel width would likely show large variations, achieving maximum width near the injection hole and tapering in size to the production hole. Lateral and axial movement of the combustion zone and thus the cavity size may be controlled to some extent by adjusting injection rate and pressure, although

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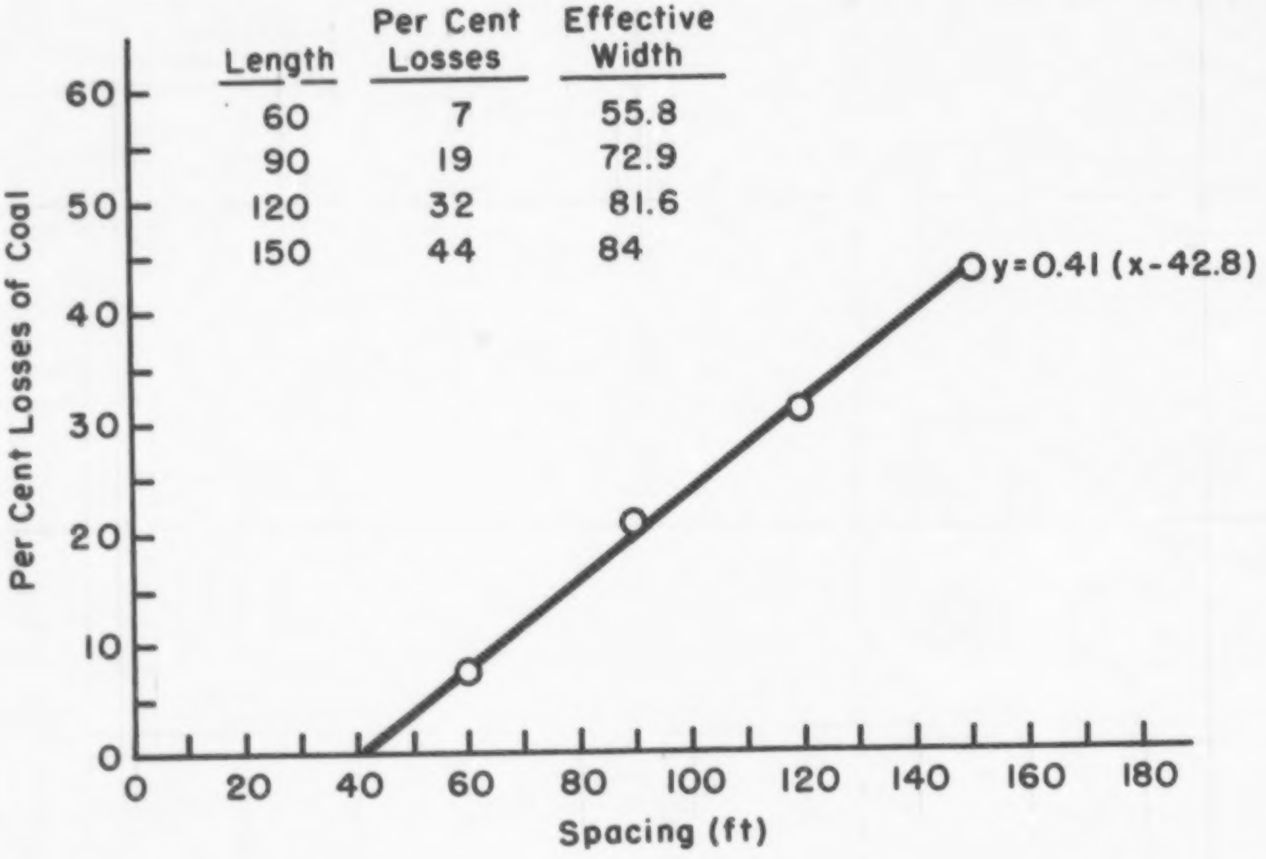

Length	Per Cent Losses	Effective Width
60	7	55.8
90	19	72.9
120	32	81.6
150	44	84

Figure 33. Relation Between Sweep Efficiency (as Per Cent Losses) vs. Well Spacing

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such control would be empirically based.

Since extensive surface subsidence would be related directly to cost in any commerical size undertaking and may be environmentally objectionable, the distance between adjacent gasification paths can be specified using an empirical formula for surface protection in longwall mining. Operational experience indicates that little predictable subsidence is likely to occur where the width of the mined panel is less than one-quarter the depth of the panel from the surface. A pillar of this size (in theory) to support the roof has sufficient bulk and mechanical strength. It is interesting to note that none of the U.S. field tests have violated this rule, assuming that the gasification width is less than the borehole spacing.

The design of barrier pillar size as used in coal mining operations has been based on engineering judgment or by one of several formulas that have been developed for this purpose, e.g., the Mine Inspectors Formula (Ashley [35]). The appropriate ratio of channel width to total width (channel and pillar), S_1, required to prevent excessive rock stress, is given by

$$S_1 = \frac{D* .25}{D* .25 + (20 + 4*T + .1*D)} \qquad (1)$$

where: * = multiplication symbol
T = Bed thickness
D = Thickness of the overburden (or depth)

S_1 can thus be thought of as the maximum sweep efficiency without subsidence. The units of all symbols and constants are in feet. The Ashley formula is incomplete in that it does not account for the strength of the rock that composes the pillar nor the overburden, hence it should be viewed as an order of magnitude prediction.

From Figure 33 the linear relationship between percentage coal losses and spacing can be used to approximate the average width of the gasification chamber, S_2, as follows (S_3 = well spacing between injector and producer):

$$S_2 = S_3*[1 - .01 * (.41 * (S_3 - 42.8))]$$

When S_3 is specified, the width or distance between parallel gasification paths is computed by combining the above relationships such that:

$$\text{WIDTH} = \frac{S_2}{S_1} \qquad (2)$$

For illustrative purposes, assuming a seam depth of 300 feet, a bed thickness of 15 feet and a spacing requirement of 150 feet, the average channel size (S_2) would be 84 feet. In order to prevent subsidence, the sum of pillar plus channel sizes would be 207 feet (S_1 = .405), yielding a very large pillar, 123 feet in width. The overall recovery thus would be 40.5%. While this design procedure is greatly oversimplified and conservative, Figure 34 indicates that the percentage of contacted coal with pillars designed by this formula varies between 39% and 66%, which appears to be reasonable.

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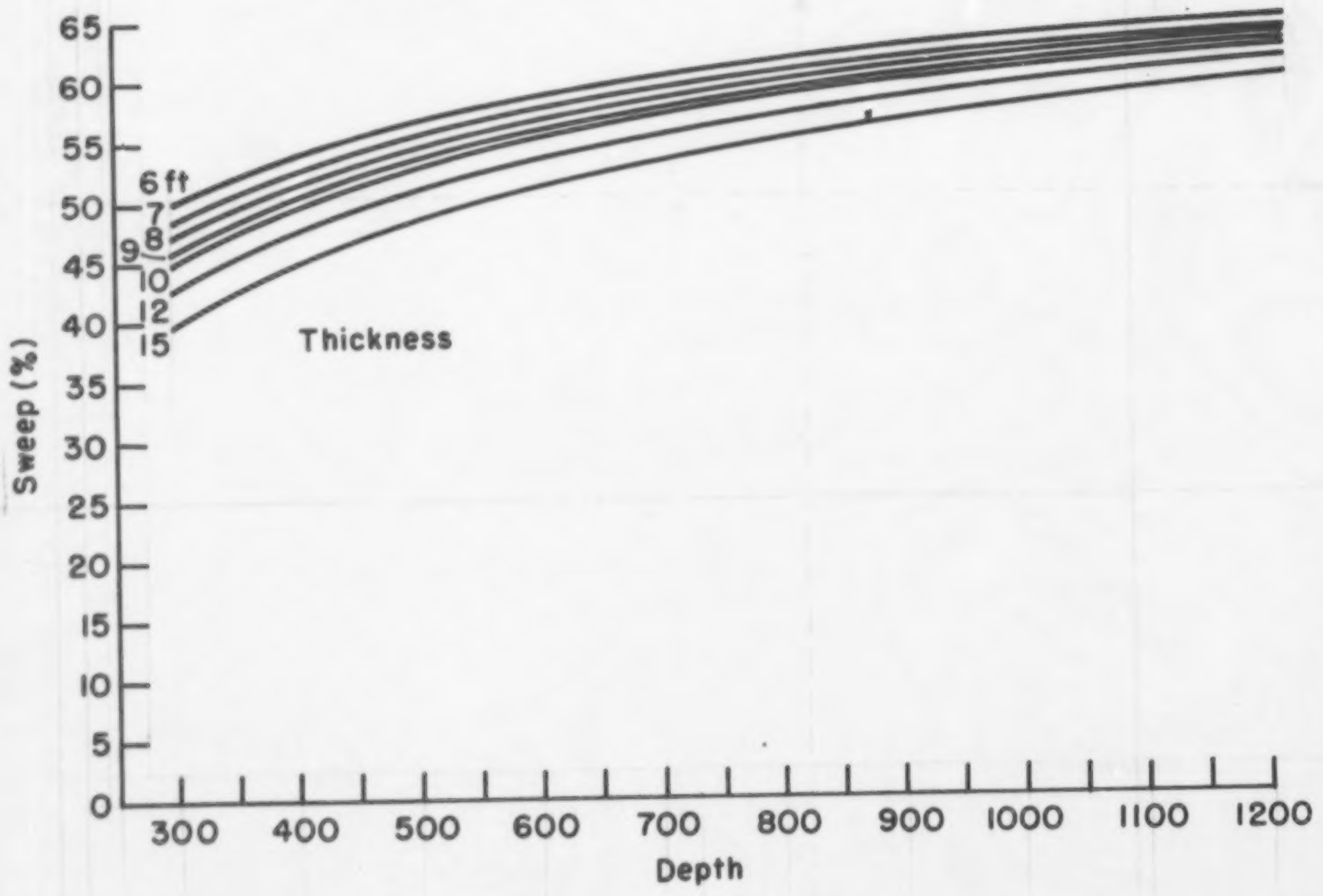

Figure 34. Maximum Sweep without Subsidence as a Function of Depth and Thickness

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in magnitude but probably not as high as economically desirable. Therefore better correlations for subsidence need to be obtained before the cost of subsidence prevention can be calculated. Thin seams yield the highest overall recoveries, due to smaller pillars.

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Section 7

ENVIRONMENTAL IMPACTS FROM UNDERGROUND COAL GASIFICATION

WATER POLLUTION

Of the possible environmental impacts of UCG, the effects on local groundwater quality may be the most significant concern in implementation of the process. Documentation exists in the literature and from current projects that pollutants are released to groundwaters when normal flow returns to a postgasification zone. Above-ground processing of product gas streams can also present water pollution control problems. Although there has been no demonstration of large-scale gas cleaning facilities in conjunction with UCG field tests, the wastewaters generated should be similar to those produced by above-ground gasification facilities.

Review of Existing Water Quality Regulations

The U.S. Congress has passed three major legislative acts on water quality which relate to in situ coal gasification: the Toxic Substance Control Act (TSCA), the Resource Conservation and Recover Act (RCRA), and the Surface Mining Control and Reclamation Act (SMCRA). At this time only SMCRA is in final form. TSCA and RCRA are in draft form and may eventually change.

TSCA--

The product gas and liquid coal products generated during UCG may fall under TCSA regulations if the substances produced are not included in the inventory of existing chemicals, and they are used as feedstocks for synthetic natural gas (SNG) or as by-product organic chemicals for sale [36]. If this turns out to be the case, then premanufacturing notification would be required before production could begin. Premanufacture notice would involve lists of available studies on the health, safety, and environmental effects of UCG. Further, EPA may restrain commerical production until further studies are complete if it determines that there are insufficient data available to assess the risk. EPA is given regulatory powers at any future time if the above data indicates that regulation is warranted [36].

RCRA--

A RCRA permit would be required for UCG disposal methods if the tar and light oils produced as byproducts are to be disposed of (either by incineration or land-fills); both of these byproducts are considered as hazardous under the act. The permit application will require extensive

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supporting data and is subject to public hearing(s). The implementation of RCRA is coordinated with regulations for Underground Injection Control (UIC) under the Safe Drinking Water Act. UCG wells are identified as Class III wells, which includes all special process injection wells [36].

SMCRA--

SMCRA regulates in-situ gasification as underground mining. Thus, a mining permit is required, which must describe the reclamation plan, the mining operation, and the environmental resources of the site. The permit requirements most significant to UCG are:

(1) Protect the hydrologic balance
(2) Protect the groundwater within and adjacent to the mine site
(3) Catalog the site environmentally

The permit for in-situ recovery activities includes all items required for a surface mine plan plus a plan for treatment of process fluid, a plan for monitoring groundwater and air quality, delineation of proposed holes, wells, and production zone, and specification for drill holes and the casing proposed.

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Ground-Water Impacts

Field and laboratory studies have identified the sources of groundwater contaminants ([37], [38], [39], [40], [41]). During the gasification phase the high temperature gases produced can migrate into surrounding strata, where cooling occurs with attendant condensation or deposition of various chemical compounds. The bulk of the condensed materials are organic compounds including light hydrocarbons, phenols, oils, and tars. The heavier organics include some polynuclear aromatic hydrocarbons (PAHs) and heterocyclic compounds. Other gaseous components that condense or are absorbed in surrounding groundwater are ammonia, carbon dioxide, hydrogen sulfide, and methane.

After gasification is completed, an ash residue remains in the burn cavity which yields soluble inorganic components to reinvading groundwaters (Figure 16). The soluble ash components can greatly increase the total dissolved solids content of the groundwater. These soluble materials include a wide array of ionic species, mainly calcium, sodium, sulfate, and bicarbonate. These components yield increases in non-specific parameters such as conductivity and total dissolved solids. The exact quantities of these materials are a function of initial coal composition, combustion temperature, water temperature, and groundwater composition. There are, however, many other inorganic materials leached into the groundwater which are of interest even though they are present in lesser quantities. These include aluminum, arsenic, barium, boron, iron, zinc, cyanide, selenium, and hydroxide. Again the exact composition depends on the variables cited above.

Organic Contaminants--

Most authors have found that the major organic groundwater contaminant in terms of mass release to groundwaters are phenolic materials. Data

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reported by Campbel et al. [41] were obtained in an extensive study of a large-scale field operation at the Hoe Creek I site in Wyoming, as shown in Table 14. It was hypothesized that the phenolic compounds were initially distributed in a ring around the burn cavity and that contaminant concentrations decreased with time. Field data indicated values of dissolved organic carbon as high as 230 mg/l in water samples taken from a well approximately two feet from the burn boundary immediately after gasification. This value dropped to 54.4 mg/l 83 days after gasification. The decrease of phenolic material concentration in groundwater as a function of distance from the burn cavity for four different points in time are illustrated in Figure 35. Possible explanations for this phenomenon are given later in this section and also in Section 9.

Groundwater samples taken from the burn cavity at a lignite gasification site at the Big Brown Steam Electric Station (Figure 6) near Fairfield, Texas (Freestone County, Figure 15), also indicated that the major organic components were phenols [40]. Table 15 presents these data and shows that other organic materials are present and also tend to decrease with time. The minor organic contaminants of concern are the PAH's and heterocyclic compounds. Similar levels of these contaminants were also found in data from reference [41].

Inorganic Contaminants

Table 14 illustrates the array of inorganic contaminants released to groundwaters as found by Campbell et al. [41]. Other studies are in agreement with these findings. Table 16 shows the changes in water quality at a site near Fairfield, Texas [38] shortly after gasification ceased. Similarly Table 17 gives the results of previously unpublished information on water quality changes shortly after gasification ceased at the Tennessee Colony site in Anderson County, Texas (see Figures 15 and 19). These data were taken by the Texas Railroad Commission which regulates in situ gasification in Texas.

The previous data are in general agreement as to which inorganic contaminants tend to increase due to ash leaching. The field data have been further supported by laboratory ash leaching experiments ([37], [38], [39], [40], [41]). Differences in results are probably due to coal/ash composition, gasifier temperatures, sampling techniques, and natural water quality. Only one parameter, pH, showed very large variations among investigators. Ash from Wyoming subbituminous coal experienced very high pH changes upon leaching. Ash from Texas lignite showed little change in pH. Again, these differences could be accounted for by the inherent differences between coal and lignite, or may be site-specific.

Fate of Pollutants

The fate of pollutants after gasification has been studied by several investigators. Since water quality is initially degraded by the contaminants discussed previously and their concentrations change with time, questions arise as to where the contaminants travel and what is their ultimate fate.

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TABLE 14: RESULTS OF WATER ANALYSIS BEFORE, DURING AND AFTER THE HOE CREEK I EXPERIMENT

Species	Conc. Units	Pregasif. baseline data[a]	Inside burn boundary (injection well) Postgasification		Outside burn boundary b							
					DW-1 (10 ft.)				EM-1 (100 ft.)			
						Post-gasification				Post-gasification		
			83 d	280 d	During gasif.	3 d	83 d	280 d	During gasif.	3 d	83 d	280 d
Alkalinity	mg/1	407 ± 30	63	-	595	693	430	-	837	686	636	410
Al^{+3}	μg/1	0 - 10	220	4	0	10	20	0	0	10	10	0
As (III)	μg/1	0 - 1	8	5	1	1	0	0	0	0	1	0
Ba^{+2}	μg/1	100 ± 100	0	500	200	600	0	0	0	0	1	0
HCO_3^-	mg/1	496 ± 40	0	48	725	845	524	340	1020	836	776	690
B (III)[c]	μg/1	86 ± 30	710	2400	90	110	360	230	90	90	70	60
Br^-	mg/1	0 - 0.1	1.0	0.6	0.2	0.3	0.7	0.3	0.0	0.1	0.1	0.2
Cd^{+2}	μg/1	0	0	1	0	0	0	0	1	0	1	5
Ca^{+2}	mg/1	36 ± 10	570	350	35	110	220	110	110	100	78	61
Co^{-2}	mg/1	0	24	1	0	0	0	0	0	0	0	0
Cl	mg/1	13 ± 5	37	19	10	10	22	13	6.6	7.4	9.5	10
CN^-	mg/1	0.00 - 0.01	0.43	0.19	7.0	48	0.14	0.05	4.0	5.0	0.01	0.01
Fe diss.	μg/1	0 - 10	30	30	380	37000	1700	1100	4400	18000	160	650
Pb^{+2}	μg/1	0 - 1	1	4	2	0	0	4	2	2	7	-
Li^-	μg/1	34 ± 5	310	170	30	50	190	130	50	50	50	40
Mg^{+2}	mg/1	10 ± 4	19	19	8.1	28	55	42	26	26	18	18
NH_4^+ as N	mg/1	0.55 ± 0.05	19	10	0.49	2.1	20	10	0.80	0.77	0.84	0.69
NO_2 as N	mg/1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

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TABLE 14: (CONTINUED)

NO_3 as N	mg/1	0.02 ± 0.01	0.01	0.00	0.19	0.01	0.07	0.04	0.01	0.01	0.02	0.00
Phenols	μg/1	1 ± 1	41	12	15	1000	340	120	83	15	2	1
K^+	mg/1	5.4 ± 0.5	57	33	4.3	7.5	25	20	7.7	7.7	6.1	5.7
Dissolved Solids	mg/1	703 ± 70	3390	2320	699	989	2020	1330	1170	1240	1050	1060
Na^+	mg/1	214 ± 15	320	280	240	250	210	260	330	320	310	300
$_4^{-2}$	mg/1	154 ± 80	2200	1550	37	67	1000	710	250	320	250	320
S^{-2}	mg/1	0.3 ± 0.2	4.0	2.8	0.7	1.1	-	-	0.3	2.6	0.6	0.0
Zn^{+2}	μg/1	224 ± 200	10	8	50	20	1200	10	120	30	20	4
CH_4	mg/1	11.5 ± 4	1.3	-	<0.2	0.4	-	-	<0.2	35.0	-	-
Conductivity	μmho/cm	1080 ± 150	3500	2720	1500	2000	2400	1610	1850	2000	1550	1525
pH		7.5 ± 0.1	10.5	9.5	7.3	7.4	7.2	7.6	7.9	7.0	7.5	6.3
T, °C		11.0 + 3	26.5	17.8	13.5	12.0	19.5	17.0	9.0	11.0	11.5	12.5

[a] The ± values indicate the approximate range of results for the seven baseline wells. The baseline data represent an average of analyses from 7 wells completed into the Felix II coal seam.

[b] Only "during" and "after" data for EM-1 (100 ft. from burn boundary) and DW-1 (10 ft. from burn boundary) are shown here since they typify the general trends observed with increasing radial distance. Also given are postgasification data for inside the burn boundary.

[c] Probably present at borate ion.

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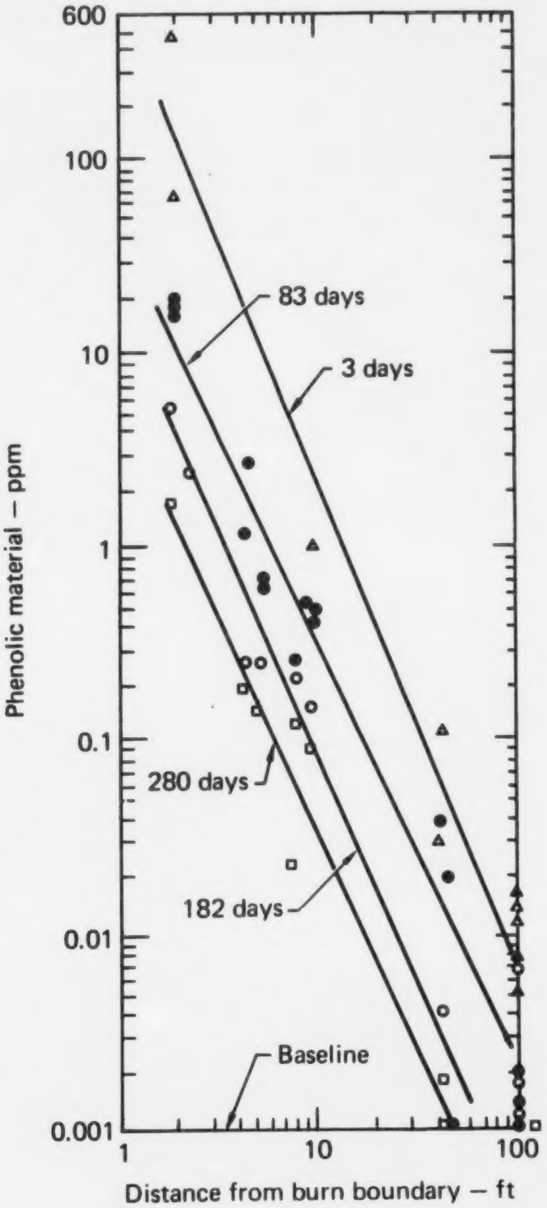

Figure 35. Concentration of Phenolic Materials at Hoe Creek I as a Function of Distance from Burn Boundary and Time After Gasification Had Ceased

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TABLE 15

ORGANIC PROFILES OF GROUNDWATER SAMPLES

Component	Groundwater after Gasification	Groundwater one year after Gasification	Groundwater before Gasification
Napthalene	70 ppb	7 ppb	2 ppb
C_1 - Alkyl	25	2	ND
C_2 - Alkyl	4	ND	ND
C_3 - Alkyl	ND	ND	ND
Biphenyl	5	ND	ND
C_1 - Alkyl	1	ND	ND
Total 2 Ring PNA's	105 ppb	9 ppb	2 ppb
Acenaphthylene	1 ppb	ND	ND
Acenaphthene	3	3 ppb	1 ppb
C_1 - Alkyl	ND	ND	ND
Fluorene	5	ND	ND
C_1 - Alkyl	ND	ND	ND
Phenanthrene	11	2	ND
Anthracene	2	ND	ND
C_1 - Alkyl	ND	ND	ND
C_2 - Alkyl	ND	ND	ND
C_3 - Alkyl	ND	ND	ND
Total 3 Ring PNA's	22 ppb	5 ppb	1 ppb
Fluoranthene	4	ND	ND
Pyrene	1	ND	ND
C_1 - Alkyl	ND	ND	ND
C_2 - Alkyl	ND	ND	ND
Chrysene/ Benzanthracene	2	ND	ND
C_1 - Alkyl	ND	ND	ND
C_2 - Alkyl	ND	ND	
Total 4 Ring PNA's	7 ppb	ND	ND
Benzo [a] pyrene	1	ND	ND
Benzopyrene Isomers	2	ND	ND
Total 5 Ring PNA's	3 ppb	ND	ND
TOTAL PNA'S	140 ppb	14 ppb	3 ppb

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TABLE 15 (Continued)

Component	Groundwater after Gasification	Groundwater one year after Gasification	Groundwater before Gasification
Phenol	52 ppm	.018 ppm	.005 ppm
C_1 - Alkyl	29	.004	.001
C_2 - Alkyl	11	.004	.001
C_3 - Alkyl	1.4	.004	ND
Indanols	1.9	ND	ND
C_1 - Alkyl	2.0	ND	ND
C_2 - Alkyl	1.3	ND	ND
Napthols	0.35	ND	ND
C_1 - Alkyl	0.37	ND	ND
C_2 - Alkyl	0.01	ND	ND
Total Phenolics	100 ppm	.02 ppm	.007 ppm
Pyridine	300 ppb	ND	ND
Alkyl Pyridines	660	ND	ND
Aniline	92	ND	ND
Benzonitrile	2	ND	ND
Quinoline	620	ND	ND
Alkyl Quinolines	330	ND	ND
Indole	170	ND	ND
Carbazole	1	ND	ND
Dibenzofuran	14	ND	ND
Dibenzothiophene	2	ND	ND
Total Heterocyclics	2,200 ppb	ND	ND
Aliphatic Hydro-Carbons	NM	ND	ND
Alkyl Benzenes	NM	ND	ND
Sulfur, S_8	ND	ND	ND
Total Organics	102 ppm	34 ppb	10 ppb

ND = Not Detected

NM = Not Measured

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TABLE 16: WATER QUALITY CHANGES IMMEDIATELY AFTER GASIFICATION (FAIRFIELD, TEXAS)

PARAMETER	BEFORE, mg^{-1}	AFTER, mg l^{-1}
Ca^{2+}	20	200
Mg^{2+}	5	15
Na^+	100	300
HCO_3^-	300	500
$CO_3^=$	2	0
$SO_4^=$	4	1150
H_2S	0.02	0.4
Cl^-	30	40
F^-	0.1	0.7
NO_3^-	-	2.0
NH_3	1.0	100
TDS	350	2300
Phenols	0.1	20
TOC	20	200
Volatile dissolved solids	-	300
CN^-	-	<0.01
CNS^-	-	<0.5
CH_4	0.42	0.16
pH	-	7.6
As	-	<0.01
Ba	-	<1
Cd	-	<0.01
Cu	-	<0.1
Cr (total)	-	<0.05
Mn	-	0.07
Hg	-	0.002
Se	-	<0.001
Ag	-	<0.05
Zn	-	<0.1
B	-	0.3

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TABLE 17: WATER QUALITY CHANGES AT TENNESSEE COLONY[a]

Component	Before[b]	After[c]
Na^+	78	136
K^+	3	27
Ca^{2+}	8	94
Mg^{2+}	2	18
HCO_3^-	275	385
SO_4	<5	625
Cl^-	9	338
F^-	0.2	5.3
NO_3^-	<0.02	0.7
TDA	293	1464
Conductivity, M-mho/cm	488	4625
Temperature °C	23.5	48
pH	8.3	8.0
Ammonia-N	0.7	163
Total Organic Carbon	2.5	790
Al	<0.1	1.1
Cu	<0.01	0.02
Fe	0.86	0.47
B	-	2.2
Se	0.01	0.034
Zn	1.8	0.02
Cn^-	-	0.008

[a] Only changes are shown. Concentrations are in mg/l except conductivity and pH.

[b] Average of 4 samples

[c] Average of 2 samples

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Data presented in the previous sections have indicated that the pollutants tend to decrease both with time and distance from the burn cavities. There are natural means by which the groundwater concentrations can be reduced ([37], [38], [39], [40], [41]). Most interpretations of field data attribute the improved water quality to adsorption and ion exchange properties of surrounding strata, precipitation reactions, dilution and dispersion by natural groundwater flow, and biological conversion reactions. It should be noted that only the last process, biological conversion, is ultimately useful in the final destruction or conversion of harmful contaminants to nonharmful products.

The conceptual model of pollutant generation and transport proposed by Campbell et al. [41] and Humenick and Novak [42] appears valid. They hypothesized that the contaminants migrate as a function of the specific interaction of the contaminants with surrounding strata. Thus, materials having little affinity for solid surfaces, such as many of the TDS components, will not be retained by surrounding strata and will travel at the rate of groundwater flow with little diminution of peak concentrations. Thus, materials with medium to large affinity for solid surfaces will travel much more slowly and have significant decreases in peak concentrations as time progresses.

These models are useful in proposing remedial methods for pollutant elimination. Modeling of pollutant dispersion is discussed in Section 8 and possible control methods are proposed in Section 9. However, more study on the fate of pollutants is needed because the mechanisms of ion exchange and adsorption (upon which the models are based) do not eliminate the pollutants from the groundwater systems. Study of biological conversion processes is also needed to establish the ultimate fate of the slow-moving contaminants.

Of particular concern is the deposition of tars and oils in the surrounding strata. Some of the components comprising the tars and oils are toxic chemicals. It appears that the solubility of these components are very low and they have high adsorption affinity for surrounding solid strata. Thus, aqueous concentrations should be low in the region of the tar deposits and their high affinity for solid surfaces should prevent rapid migration into the water phase. Considering solubility and adsorption only, it should take a very long time (e.g., years) before the source of pollution is dispersed. The study of the fate of these components appears to be of major importance relative to permitting, regulations, and restoration.

Effect of Air Vs. Oxygen Injection

An oxygen-blown system will ordinarily achieve higher temperatures than an air-blown system. This is because of the higher rate of combustion relative to the endothermic char-steam reaction. The temperature can be controlled by steam-injection, as in a non-slagging Lurgi gasifier, although thermal efficiency is increased by higher gasification temperatures. An important related question is how pyrolysis products, which ultimately may become groundwater pollutants, vary depending upon injection gas and/or

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gasification temperature. The only environmental data which allows comparison of tar-water condensates for air vs. oxygen injection have been reported by Humenick and Mattox [38]. They found that the level of phenols in groundwater was higher for oxygen gasification than for air gasification (Tennessee Colony). More data are needed to quantify the environmental trade-offs between air and oxygen injection.

Above-Ground Wastewaters

Wastewaters generated above ground arise principally from the gas cooling step, causing condensation of water, oils, and tars from the gas generated in situ. The condensate may contain three phases - water, oil, and solids. The water phase can contain high concentrations of phenols and other organic compounds, ammonia, hydrogen sulfide, carbon dioxide and various inorganic compounds. Limited data available from the literature on tar/water compositions produced by in situ gasification are shown in Tables 18, 19, and 20. Table 18 illustrates the distribution of volatile organics in the tar/water condensate and compares it to that found in groundwater about five feet from the burn cavity at Hoe Creek I [41]. The significance of these data is in the high concentration of organics in the condensed water phase, as expected.

TABLE 18: VOLATILE ORGANICS IN TAR/WATER

	Condensate and Groundwater		
Compounds	Process tar, ppm	Process water, ppm	Groundwater ~5 ft. from burn (DW-5), ppm
Acetone	31.0	2.23	0.016
n - Hexane	250	0.211	NR
Methyl ethyl ketone	NR[a]	0.044	0.010
Benzene	272	4.32	0.192
Thiopene	5	0.241	0.007
Methyl isopropyl ketone	NR	0.089	NR
Toluene	1018	1.081	0.068
Methyl thiophene isomers	12	0.106	0.237
Ethyl benzene	100	0.041	0.002
Xylene isomers	1050	0.203	0.010
Napthalene	13920	1.707	0.0004
Biphenyl	1390	0.031	NR
Indan	533	0.072	NR
Indene	833	0.140	NR
Styrene	107	0.055	0.004

[a] NR = not reported.

Tables 19 and 20 show analyses of tar and water condensate samples taken from the Tennessee Colony site in Texas. These analyses give information about the heavier organic compounds. Table 19 shows the analyses for two tar samples where 58 to 67 per cent of the organic matter is accounted for. The remaining, unaccounted fraction is presumably heavier compounds. It can be seen that PAH's (polynuclear aromatic hydrocarbons) make up 10.5 to 14 percent of the tar and heterocyclic compounds 0.62 and 0.72 per cent. These fractions contain toxic and carcinogenic substances.

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TABLE 19: ORGANIC COMPONENTS IN CONDENSED PRODUCT TARS

Component	Tar I	Tar II
Napthalene	.50%	.61%
C_1 - Alkyl	.69	.52
C_2 - Alkyl	1.2	1.2
C_3 - Alkyl	1.3	.94
C_4 - Alkyl	.67	.42
Biphenyl	.29	.28
C_1 - Alkyl	.005	.040
Total 2 Ring PAH's	4.7%	4.1%
Acenaphthylene	0.89%	ND
Acenaphthene	.53	.11
C_1 - Alkyl	.11	.11
Fluorene	.52	.41
C_1 - Alkyl	.36	.25
Phenanthrene	1.7	1.4
Anthracene	.63	.50
C_1 - Alkyl	.95	.71
C_2 - Alkyl	.58	.44
C_3 - Alkyl	.48	.24
Total 3 Ring PAH's	6.0%	4.2%
Fluoranthene	.50%	.26%
Pyrene	.79	.43
C_1 - Alkyl	.55	.38
C_2 - Alkyl	.27	.19
Chrysene/Benzanthracene	.58	.28
C_1 - Alkyl	.20	.32
C_2 - Alkyl	.078	.13
Total 4 Ring PAH's	3.0%	2.0%
Benzo[a]pyrene	.12%	.004%
Benzopyrene Isomers	.35	.14
Total 5 Ring PAH's	.47%	.19%
Total PAH's	14 %	10.5 %

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TABLE 19: (CONTINUED)

Component	Tar I	Tar II
Phenol	.17%	.77%
C_1 - Alkyl	.52	1.3
C_2 - Alkyl	.89	1.3
C_3 - Alkyl	.75	.84
C_4 - Alkyl	.27	.31
Indanols	.41	.54
C_1 - Alkyl	.53	.52
C_2 - Alkyl	.62	.52
Napthols	.70	1.1
C_1 - Alkyl	1.3	1.8
C_2 - Alkyl	1.2	1.5
Total Phenolics	7.4 %	10.5%
Pyridine	ND	ND
Alkyl Pyridines	ND	ND
Aniline	ND	ND
Benzonitrile	ND	ND
Quinoline	.074	.059
Alkyl Quinolines	NM	NM
Indole	.052	.075
Carbazole	.14	.095
Dibenzofuran	.33	.29
Dibenzothiophene	.12	.10
Total Heterocyclics	.72%	.62%
Aliphatic Hydrocarbons	34.	43.
Alkyl Benzenes	2.0	2.0
Sulfur, S_8	ND	ND
Total Organics	58 %	67%

ND = Not Detected

NM = Not Measured

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Table 20 shows the analysis of water condensate samples. Water I and Water II are samples separated from Tar I and II in Table 19. A similarity can now be seen between condensed water and groundwaters. Phenols again comprise the major portion of the organic material in the water condensate, while the other less-soluble organics such as PAH's occur in lower concentrations. For example, phenols ranged from 116 to 530 mg/l while PAH's were between 110 and 200 mg/l.

TABLE 20: ORGANIC COMPONENTS IN CONDENSED PRODUCT WATER

Component	Condensed Product Water I	Condensed Product Water II
Napthalene	78 ppb	46 ppb
C_1 - Alkyl	10	9
C_2 - Alkyl	5	5
C_3 - Alkyl	2	1
C_4 - Alkyl	ND	ND
Biphenyl	1	1
C_1 - Alkyl	ND	ND
Total 2 Ring PAH's	96 ppb	62 ppb
Acenaphthylene	2	1
Acenapthene	10	6
C_1 - Alkyl	2	ND
Fluorene	5	1
C_1 - Alkyl	1	ND
Phenanthrene	55	10
Anthracene	5	1
C_1 - Alkyl	2	NM
C_2 - Alkyl	ND	ND
C_3 - Alkyl	ND	ND
Total 3 Ring PAH's	82 ppb	19 ppb
Fluoranthene	3	2
Pyrene	4	5
C_1 - Alkyl	ND	2
C_2 - Alkyl	ND	ND
Chrysene/Benzanthracene	5	10
C_1 - Alkyl	1	1

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TABLE 20: (CONTINUED)

Component	Condensed Product Water I	Condensed Product Water II
4 Ring PAH's (Cont.)		
C_2 - Alkyl	ND	ND
Total 4 Ring PAH's	13 ppb	20 ppb
Benzo [a] pyrene	2	2
Benzopyrene Isomers	7	8
Total 5 Ring PAH's	9 ppb	10 ppb
Total PAH's	200 ppb	110 ppb
Phenol	350 ppm	50 ppm
C_1 - Alkyl	98	38
C_2 - Alkyl	40	19
C_3 - Alkyl	6.0	4.0
C_4 - Alkyl	4.5	0.74
Indanols	5.9	0.96
C_1 - Alkyl	6.2	0.72
C_2 - Alkyl		
Napthols	8.0	0.54
C_1 - Alkyl	10.	0.64
C_2 - Alkyl	2.4	0.32
Total Phenolics	530 ppm	116 ppm
Pyridine	280 ppb	49 ppb
Alkyl Pyridines	100	500
Aniline	50	20
Benzonitrile	ND	4
Quinoline	930	150
Alkyl Quinolines	410	60
Indole	50	100
Carbazole	590	100
Dibenzofuran	25	10
Dibenzothiophene	20	12
Total Heterocyclics	2460 ppb	1000 ppb

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TABLE 20: (CONTINUED)

Component	Condensed Product Water I	Condensed Product Water II
Aliphatic Hydrocarbons	NM	NM
Alkyl Benzenes	NM	NM
Sulfur, S_8	ND	36 ppm
Total Organics	532 ppm	117 ppm

ND = Not Detected NM = Not Measured

Analysis of tar/water condensates is not well defined for in situ processes at this time. Data that are lacking include characterization of the inorganic contaminants in the water phase and quantification of the amounts of water and tar generated as a function of gasifier operating conditions.

AIR POLLUTION DURING UCG

While the water pollution impact from underground coal gasification is localized in nature, the air quality considerations in UCG have much broader geographical ramifications. This is because in situ gasification offers the possibility of actually reducing regional air quality impacts, when compared to the alternative of strip mining and burning solid fuel in a conventional steam-electric plant. Therefore in this sub-section we shall not only analyze local emissions from a UCG facility but also consider the larger question of how large-scale regional use of lignite will affect the attractiveness of in situ gasification.

Probable Locations for UCG Plants in Texas

By its very nature the underground coal gasification plant must be located where the coal formations occur. Texas lignite formations have been mapped and evaluated (see Section 5) from the standpoint of their suitability for in situ gasification. From considerations of the grade of lignite, thickness, uniformity and continuity of the seams, overall geometry of the lignite-bearing of the geologic units, occurrence of faulting, nature of the underburden and overburden, orientations of aquifers, and direction of groundwater flow, certain regions appear to be suitable for locating future in situ lignite gasification plants, as discussed in Section 5.

The potential regions for UCG location cover about 17 counties with eight more adjacent counties being peripheral to the lignite-bearing units and offering the possibility of alternate locations. All the regions lie close to the densely industrialized areas on the Gulf Coast. The potential UCG areas offer a definite location advantage to the industries on the Gulf Coast, since major addition of new large industries on the Gulf Coast may be highly unlikely in view of environmental constraints there. Of course, this implies that any synthetic gas or liquids produced at UCG sites must be transported by pipeline to the demand points.

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Air Quality Requirements in Texas

The Federal Clean Air Act as Amended, 1977, specifies that ambient air has to conform to certain national ambient air quality standards (NAAQS) everywhere in the country. The standards exist for the following man-made or caused pollutants: carbon monoxide, non-methane hydrocarbons (which cause the formation of ozone, a photochemical oxidant), oxides of nitrogen, sulfur dioxide, suspended particulate matter, and lead. In addition, national standards exist for hazardous air pollutants, namely, asbestos, beryllium, mercury and vinly chloride monomer. The Federal Government requires the state governments to administer the provisions of the Clean Air Act.

The State of Texas has its own Clean Air Act and a set of regulations that must be met throughout the state. For the purpose of administration, the state has been divided into 12 air quality control regions (AQCR). The areas in the state which are presently in violation of the NAAQD are classified as non-attainment. The State Government is required to have a federally approved state implementation plan (SIP) which outlines its phased abatement program to convert the non-attainment areas in the state for the various pollutants and the State Air Quality Control Regions (AQCR) are shown in Figure 36. The regions considered for UCG siting are all in the attainment areas, although some are very close to the non-attainment areas.

Air Quality Regulations Applicable to New Industry

A large number of regulatory approvals, federal and state, are required for the siting and construction of new industries or for the expansion of existing plants. These fall variously under the Federal Clean Air Act As Amended (August, 1977), the Federal Water Pollution Control Act (1972), the Resource Conservation and Recovery Act (1976), the Power Plant and Industrial Fuel Use Act (1978), and the National Environmental Policy Act (1970). The type of industry determines the different regulations under which it would fall and also the various regulatory approvals required prior to its construction. Apart from these federal laws there exist state regulations which must be satisfied.

The Clean Air Act ([43], [44], [45]) classifies the regulatory approvals required under it into two groups. The first, the Prevention of Significant Deterioration (PSD) permit, applies to new industries or plant expansions located in the attainment areas. The second, the Emissions Offset (EO) permit, applies to those proposed in the non-attainment areas. As seen in Figure 36, future underground lignite gasification locations would be in the attainment regions and hence will be subject to PSD regulations for Class II regions.

PSD Permit Requirements

Since all future UCG facilities and the industries fed by UCG are likely to be subject to the PSD requirements, these will be briefly outlined here. The PSD requirements form the most restrictive of the various regulatory compliances required for a new project. New plants are subject to PSD requirements if the potential emissions of any regulated pollutant exceed 100 tons/

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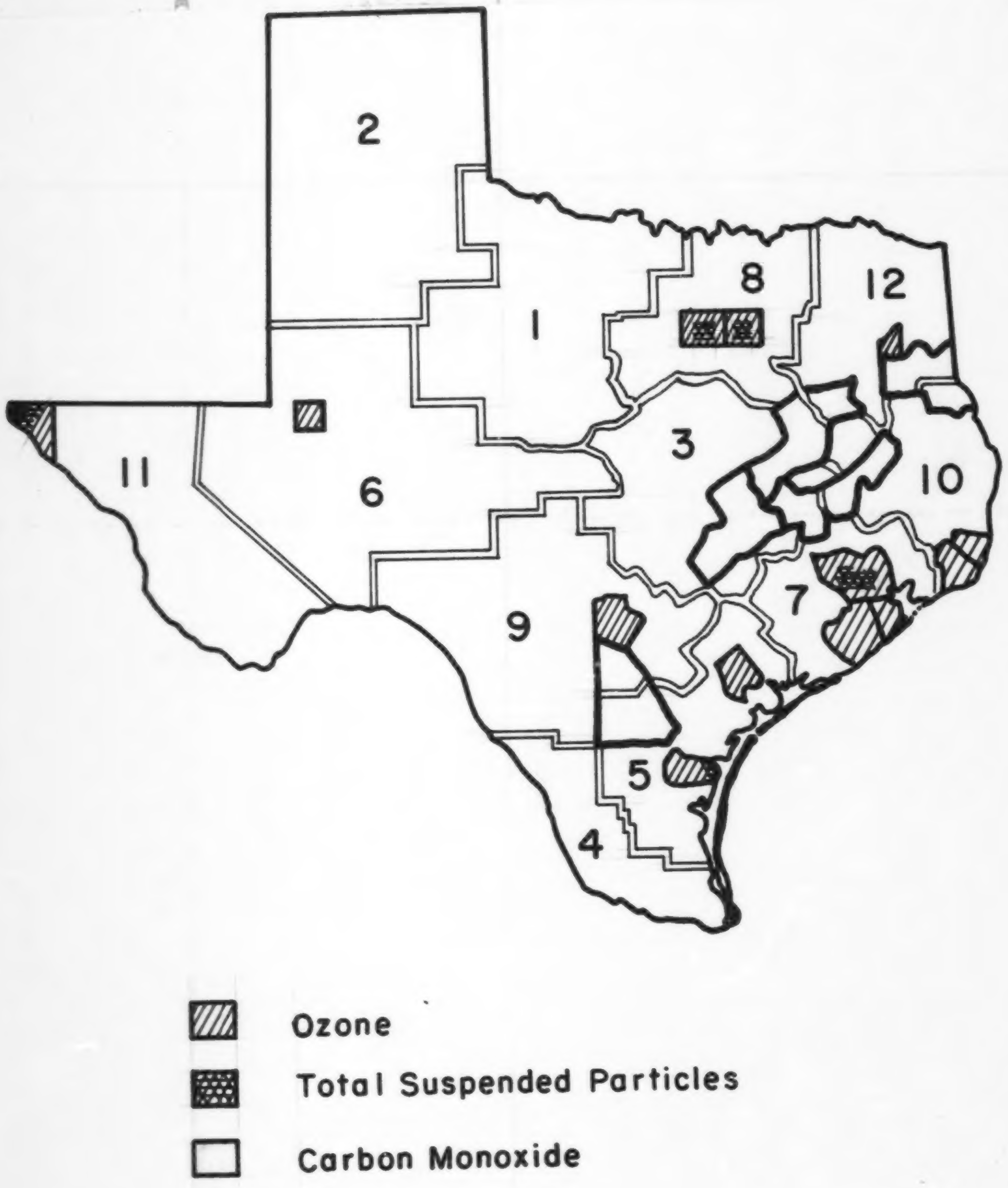
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Ozone
Total Suspended Particles
Carbon Monoxide

Figure 36. TACB Air Quality Control Regions and Non-Attainment Regions (Five Deep Basin Lignite Blocks Outlined)

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year for plants within the 28 specified industrial categories or if the potential emission exceed 250 tons per year for any other plant. Currently the PSD requirements cover only two pollutants: sulfur dioxide and total suspended particles. The term "potential emissions" refers to raw emission levels measured before the application of control devices such as dust collectors, scrubbers, precipitators, etc., and includes fugitive emissions.

Sources subject to PSD but with actual emissions less than 50 tons/year after applying its pollution control system qualify for a simplified review, omitting the requirement to demonstrate compliance with the PSD increment and to install the best available control technology, although they must still comply with the applicable new source performance standards (NSPS) or the state implementation plan (SIP) requirements. Such smaller sources, which may include emissions from UCG field tests, are also exempt from the need to conduct an ambient impact analysis or to submit data supporting an ambient air quality analysis in order to obtain preconstruction approval. New source performance standards do not as yet exist for underground coal gasification [46]. However, if a downstream plant such as a steam/power generation unit is also provided at the UCG site, the NSPS for the latter unit may apply to the entire project.

Pollutant Emissions from UCG

The amounts of air pollutants produced in a UCG operation will vary with the production capacity, the operating conditions, and the nature of coal being gasified. The concentrations of pollutants produced by the raw emissions (i.e., those without any control devices) have been measured at the field tests conducted at Hanna, Wyoming [47]. The measurements show the presence of the same pollutants obtained from above ground gasification of coal (such as the Lurgi gasifier). These pollutants include H_2S, COS, CS_2, ammonia, liquid byproducts, particulates and trace metals.

The pollutant monitoring at Hanna (Test II, 1976) showed the presence of trace amounts of ammonia (0.13-0.28 ppm), HCN (0.4-10 ppm), COS (0.5-3 ppm) and CS_2 (2.2-9.8 ppm) in the raw gas [47]. No data on polynuclear aromatic compounds was reported. The particulate emissions were measured for both the total concentration and the trace components present, such as mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), selenium (Se), sodium (Na), potassium (K), lithium (Li), vanadium (V), and calcium (Ca). Of these elements only Na and Ca were seen to approach or exceed 1 ppm concentration in the raw gas. The monitoring indicated that no unexpectedly high concentrations of any species were produced. Hence no unforeseen problems should be encountered in the raw gas cleanup.

The particulate size distribution varied widely in mean and standard deviation during the Hanna test [47]. In some cases the median particle size was submicron ($d_{50}<1\mu$) while at other times the particle size distribution was somewhat similar to the loading in stack gas from a solid coal-burning facility ($d_{50}=15\mu$). The total loading varied from .023 to 3.44 lb/10^6 Btu (10 to 1490 ng/J) The large variation in loading is probably due to roof falls which occur from time to time, somewhat precipitously. When the system is operating favorably, many particulates are filtered out under-

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ground. It should be noted that the Revised New Source Performance Standard for particulates from coal-fired power plants is 0.013 lb/10^6 Btu (5.6 ng/J).

Sulfur Compounds--

One of the interesting results of the Hanna field test is that the sulfur balance indicated an appreciable amount of sulfur is left underground. It has already been mentioned that large amounts of sulfates are found in the cavities after gasification, yet this seems inconsistent with the concept of gasification as a reducing process. In the reducing environment, it is expected that sulfur will be found as H_2S, COS, FeS (pyritic sulfur), and elemental sulfur. Therefore, a closer look at the transformations of sulfur expected during UCG is warranted.

Actually the coal and coal ash is exposed first to pyrolysis, and then to gasification, both reducing environments. However, the final state is oxidation, due to the moving combustion zone. Therefore, whatever sulfur is left behind after pyrolysis and gasification is partially oxidized. This sulfur could become SO_2 if it were not for the affinity of components of the ash for sulfur and SO_2. For example, calcium and magnesium carbonates in the ash react with SO_2, forming $CaSO_4 \cdot MgSO_4$.

Workers at Lawrence Livermore Laboratory [39] devised an experiment to simulate leaching conditions following UCG. A low-rank subbituminous coal containing 0.65% (as received basis) total sulfur initally was slowly pyrolyzed, then carefully ashed. Samples of this ash were heated in air in a furnace to either 1000, 1100, or 1200°C. These ash samples were then leached with groundwater as described in the report, and the following maximum sulfate concentrations were obtained:

	Field (Baseline)	1000°C	1100°C	1200°C
SO_4^{2-} conc. (ppm)	220	2193	2010	1667

A plot of sulfate concentration versus volume of leachate was made for each ash sample. The resulting curve was integrated, thus giving an estimate of the maximum amount of sulfate released by the ash. This procedure resulted in a value of 0.96 moles SO_4^{2-} released/kg of ash for the 1000°C ash. (No values were reported for the 1100 or 1200°C ash, except for the maximum sulfate concentrations given previously).

In an earlier study, researchers at the U.S. Bureau of Mines ashed three different samples of North Dakota lignita and lignite char at various temperatures ranging from 400 - 900°C [48]. After ignition to residual ash, the following date were reported:

TABLE 21: DISTRIBUTION OF SULFUR FORMS ON IGNITION OF GASIFICATION CHARS AND LIGNITES FROM DAKOTA STAR MINE

Sample and run number	Total sulfur, percent	Sulfur fixed on ignition	Sulfur removed on ignition	Percent	
				Total sulfur fixed	Fixed sulfur as water-soluble sulfate
Lignite 11L.....	0.99	0.76	0.23	77	91
Lignite 11M.....	1.00	0.65	0.35	65	100
Lignite 12H.....	0.88	0.74	0.14	84	96
Char 11L........	4.43	4.18	0.25	95	78
Char 11M........	4.50	4.15	0.35	92	77
Char 12H........	3.54	3.42	0.12	97	75

The ash content of each lignite was reported to be:

Lignite 11L	7.9% ash
Lignite 11M	6.9% ash
Lignite 12H	6.1% ash

Using data from Table 21, the amount of sulfates which would be formed after gasification and oxidation of 1 kg. of raw lignite can be calculated. For example, for lignite 11L, one finds

$$\frac{\text{Moles sulfate formed}}{\text{kg lignite}} = \left(\frac{9.9\text{ g S init.}}{\text{kg lignite}}\right)\left(\frac{0.77\text{ g S fixed}}{1.00\text{ g S init.}}\right)\left(\frac{0.91\text{g S as }SO_4^{2-}}{1.00\text{ g S fixed}}\right)$$

$$\times\left(\frac{1\text{ mole S}}{32.06\text{ gS}}\right)\left(\frac{1\text{ mole }SO_4^{2-}}{1\text{ mole S}}\right) = \frac{0.216\text{ mole }SO_4^{2-}}{\text{kg lignite}}$$

Assuming all of the sulfates formed are eventually leached into the groundwater, the maximum moles of sulfate released/kg ash is calculated to be

$$\frac{SO_4^{2-}\text{ released}}{\text{kg ash}} = \left(\frac{0.216\text{ mole }SO_4^{2-}}{\text{kg lignite}}\right)\left(\frac{1\text{ kg lignite}}{0.079\text{ kg ash}}\right)$$

$$= 2.7\text{ moles }SO_4^{2-}/\text{kg ash}$$

Similar calculations for lignites 11M and 12H give values of 2.9 and 3. 6 moles SO_4^{2-}/kg ash, respectively.

Comparing the results of the preceding calculations with the value of 0.96 moles SO_4^{2-}/Kg ash obtained by LLL [39] shows that three to four times more sulfate may have been formed during the Bureau of Mines [48] ashing procedure than in the LLL experiments. Differences in ashing procedure, mineral content of the coal, coal rank (subbituminous in LLL vs. lignite in U.S. B.M.), and initial sulfur content (0.65% in LLL vs. 0.88 - 1.00% in U. S.B.M.) as well as the forms of sulfur are some of the factors which may have contributed to the variation in sulfate formation between the two studies. Obviously, much more data need to be gathered before any reliable estimates of sulfate released after in situ gasification of a given coal can be made.

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Very little data are available on the sulfur compounds in the product gases from an actual or simulated UCG process. Gangwal et al., [49] states that H_2S is present at about 5000 ppm in the product stream of a semi-batch coal gasifier, but no detailed data are given. Stinnett et al., [50] used the principle of thermodynamic free-energy minimization to predict sulfur species distribution in the product gas from a typical "third generation coal gasification process". Their calculations showed that H_2S, COS, and S_2 will be the dominant sulfur-containing species in the equilibrium gas mixture. The relative amount of each compound present depends upon such variables as temperature, pressure, and especially the composition of the oxidation mixture (i.e., gasifier feed). In addition to the three dominant sulfur species mentioned above, significant amounts of CS_2 and SO_2 can also be found under certain conditions. For example, when oxygen is extremely scarce (50% of stoichiometric), a significant amount of CS_2 can be found, since more of the carbon combines directly with sulfur rather than being oxidized to CO or CO_2. However, at 55% oxygen, the CS_2 concentration becomes negligible in comparison to the H_2S and COS concentrations. As the oxygen content is increased further, the COS and SO_2 concentrations increase and gradually replace H_2S.

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The U.S. Bureau of Mines investigated the carbonizing properties of North Dakota lignite and collected data for the evolution of H_2S and the retention of sulfur by the char on carbonization [51]. The results with sulfur varied widely and hence were inconclusive. The fraction of total sulfur appearing in H_2S ranged from 21.1 to 70.0%. No relationship was found between either evolution or retention of sulfur and other chemical or physical properties of the coal, such as moisture, volatile matter, ash, carbon-hydrogen ratio, oxygen, or total-sulfur contents [48].

Gas Cleanup--

The UCG fuel gas is qualitatively similar to that produced by an above-ground gasifier, and must be cleaned to some degree before it can be utilized for power generation or as a chemical feedstock. The extent of the cleanup required will vary with the end-use for the gas. However, since fuel sulfur and nitrogen compounds appear in reduced form (not oxides), these potential pollutants can readily be scrubbed from the gas stream. The cleanup schemes possible for using the UCG gas for power generation by the gas turbine, steam turbine or a combined cycle plant have been discussed in several references [52], [53]. Figure 37 [52] shows a typical cleanup system for UCG fuel gas. The fuel gas must be quenched with a water wash to remove most of the particulates, trace metals, liquid by-products and ammonia. This can be done using skid mounted equipment located near the production wells, thus eliminating many by-products before pipeline transport to the main cleanup plant (desulfurization), which is centrally located. The use of waste heat exchangers and gas coolers, as shown in Figure 37, will depend upon the gas exit temperature, which may vary from 150°C to 300°C. The incentive for heat recuperators in UCG is much lower than for a Lurgi gasifier, there the product gas leaves the gasifier at around 700°C.

The desulfurization step can also include removal of CO_2, which may be of interest as a by-product. The H_2S removed must be passed to a Claus or Stretford plant to produce elemental sulfur. The specific desulfurization

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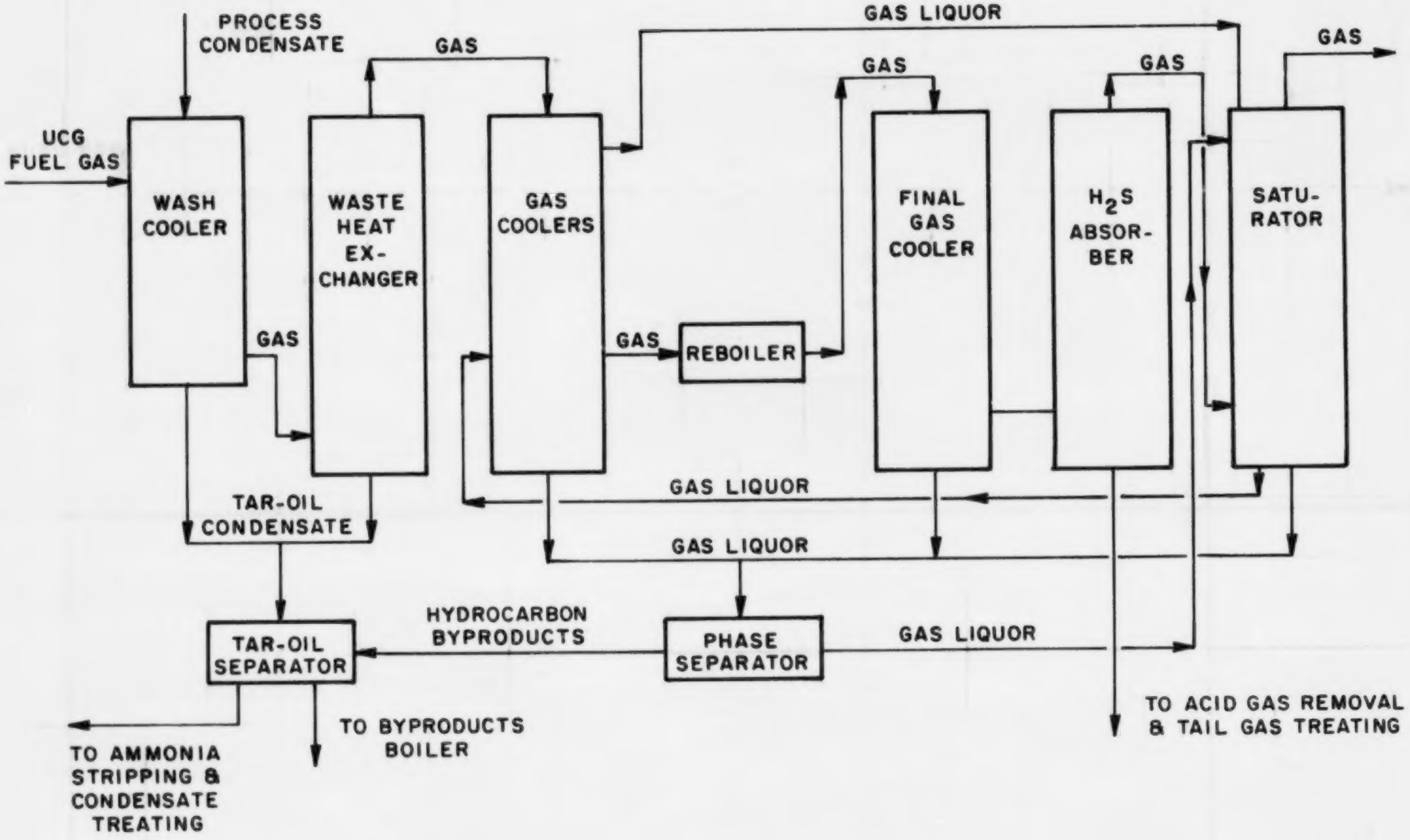
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GAS
REBOILER
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FINAL
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SATU-
RATOR
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GAS LIQUOR
TAR-OIL
CONDENSATE
TAR-OIL
SEPARATOR
HYDROCARBON
BYPRODUCTS
PHASE
SEPARATOR
GAS LIQUOR
TO AMMONIA
STRIPPING &
CONDENSATE
TREATING
TO BYPRODUCTS
BOILER
TO ACID GAS REMOVAL
& TAIL GAS TREATING

Figure 37. UCG Gas Cleanup System

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process used will depend upon the pressure of the fuel gas (the gas will need to be compressed if a high temperature gas turbine is to be used or if it is to be converted to methanol) [52].

Environmental Impact on UCG

While the degree of cleanup of the UCG gas will be determined by the type of use, it is evident from the field tests and the various studies conducted so far that conventional control technology should be adequate to remove the pollutants and to reduce the emmissions. However, it is the overall environmental impact of UCG coupled to a power generation plant or a chemical plant that is important to consider, whether such a plant is located at the UCG site or farther away. The assessment of the impact of a chemical plant using medium Btu gas as the feedstock is complicated by the variety of processes which may require different degrees of preprocessing of the gas. The impact of UCG on power generation versus direct combustion of coal is easier to assess and is discussed below.

Edgar et al. [54] and Cooper et al. [55] have discussed the impact of increased coal utilization for power generation on the ambient air quality in the Houston-Galveston metropolitan area, which is the most industrialized region in the state. The estimated pollutant emissions from power generation plants in 1985 in this region are shown in Table 22, which shows the comparative emissions from direct combustion of lignite or coal and from combustion of the low or medium Btu gas from a UCG plant. The emissions from a UCG-based plant are significantly lower for all the major pollutants than for a conventional power plant with stack gas cleanup. This is because nitrogen and sulfur compounds and particulate matter in the gas are removed prior to combustion. Thus, from an environmental standpoint, for the Houston-Galveston metropolitan area, the construction of new plants based on burning a medium Btu gas obtained through pipeline from the UCG sites, or via conventional gasifiers, is favored. Low Btu gas is only feasible for use at the mine-mouth, but the electrical power produced could be transmitted to the Gulf Coast.

If, however, the power generation plants are located at the lignite deposits themselves and the power is transmitted to the consuming centers on the Gulf Coast, there may be shifts in the statewide air quality patterns. While the consuming areas will experience little or no adverse environmental impact, the predominantly rural areas where lignite deposits exist may experience some problems. This of course will also be tied to medium and long range transport of pollutants in the atmosphere. A large number of lignite-based power plants are indeed planned for the future (up to 1989) at various locations along the Texas lignite belt. These are shown in Figure 38 along with the plants which will use western (non-Texas) coals. All the lignite-based plants are presently scheduled to use conventional pulverized coal boilers.

Regional Environmental Considerations

Many of the planned power plants shown in Figure 38 will be located in the regions which have the highest potential for locating underground gasification sites. In the light of the relative extents of pollution

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TABLE 22: COMPARATIVE END USE AIR POLLUTANT EMISSIONS FROM COMBUSTION OF MEDIUM BTU GAS (UCG) AND DIRECT LIGNITE/COAL COMBUSTION HOUSTON-GALVESTON AIR QUALITY REGION(1985) [54]

	Incremental emission rate -- tons/year[1]			Relative Increase, %		
Air pollutant	Direct combustion	UCG[5]	Regional total (1973)[4]	Direct combustion	UCG	Reduction obtained by gasification
particulate matter	20,000	1,800	224,000	9.1%	0.8%	90.8%
sulfur oxides	33,600[2] (224,000[3])	100	195,000	17.2% (114.6[3]%)	<0.1%	99.7%
nitrogen oxides	172,000	57,000	299,000	57.6%	19.2%	66.6%

Notes:

[1] based on additional $19\text{x}10^6$ tons coal/year required in 1985 to meet energy demands

[2] 85% SO_2 removal

[3] uncontrolled SO_2 emissions

[4] regional emission totals for Region 7 courtesy of Texas Air Control Board

[5] based on emissions from combustion of natural gas (EPA AP-42, "A Compilation of Air Pollutant Source Emission Factors", EPA Office of Air Quality and Standards, Research Triangle Park, N. C., 1977)

R169 "Ground-water Resources of Rains and Van Zandt Counties, Texas." April, 1973.

R185 "Ground-water Resources of Brazos and Burleson Counties, Texas." June, 1974.

R186 "Ground-water Resources of Grimes County, Texas." September, 1974.

R210 "Ground-water Resources of the Carrizo Aquifer in the Winter Garden Area of Texas." Volumes I and II. April, 1977.

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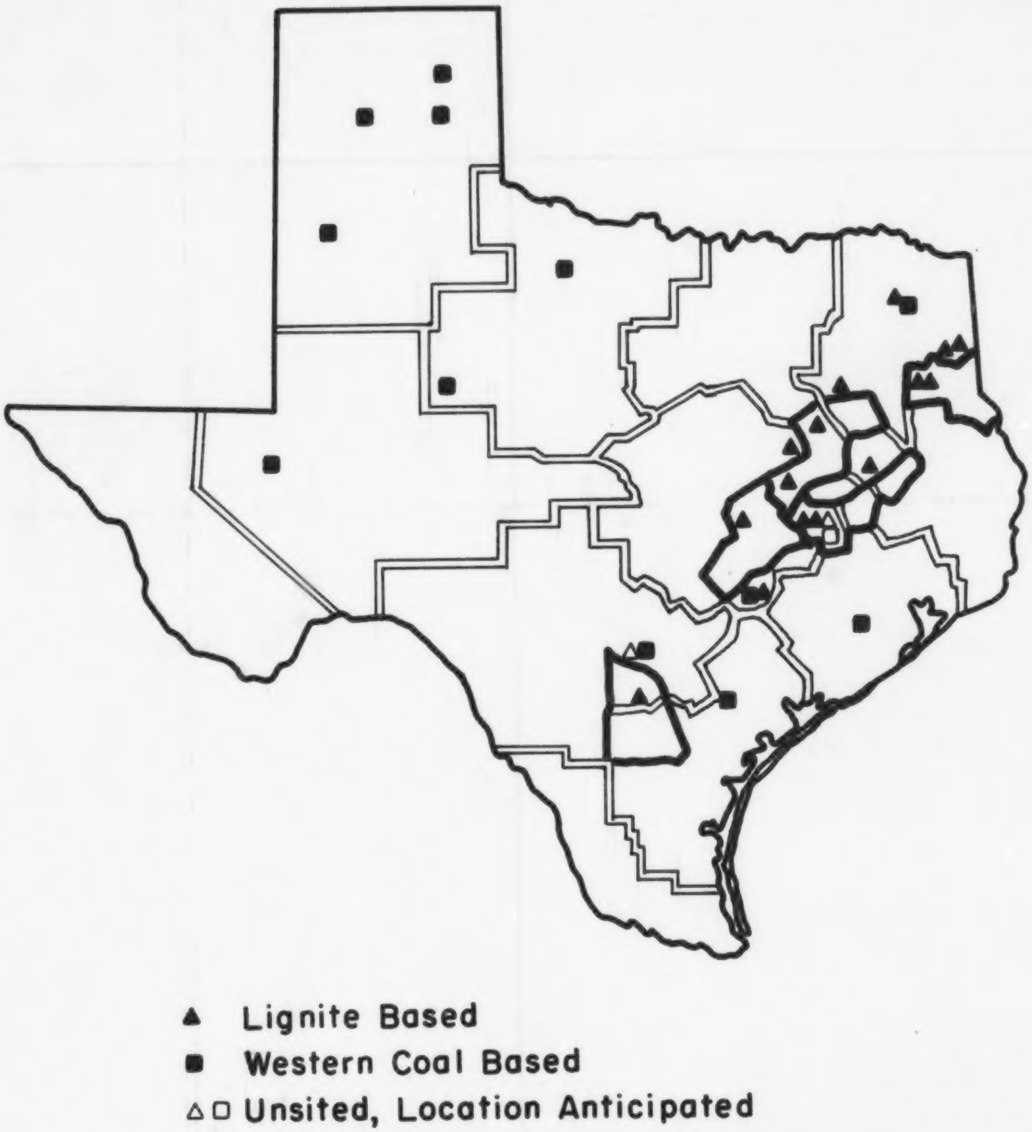
▲ Lignite Based
■ Western Coal Based
△□ Unsited, Location Anticipated

Figure 38. Lignite and Western Coal-Fired Electric Power Generating Stations (Projected up to 1989) Deep Basin Lignite Blocks and TACB Regions Outlined

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shown in Table 22, the actual emissions in these regions can be significantly reduced if UCG-based power plants are considered as an alternative to future conventional lignite or coal plants.

In order to ensure that the five regions for potential UCG locations in Figure 36 are indeed suitable for siting of UCG facilities based on air quality considerations, the nature of the existing industries and the emission sources presently located in these regions have been examined. As mentioned before, all five regions are classified as attainment regions with respect to all major pollutants. Most of the existing sources in the regions can be considered as having small effects on the environment. Many also emit small quantities of pollutants for which regulations do not exist at present, such as trace metals, inorganic acids and bases, hydrogen sulfide and so on. Under the PSD approval requirements, all the regions except region 4 are classified as Class II, i.e., permitting moderate industrial growth within limits of PSD increments of pollutant concentrations in the ambient air. Region number 4, consisting of Walker, Grimes, Trinity, Houston, Madison, and Brazos counties, includes portions of the Crockett and Sam Houston National Forests. Thus UCG sites closer to these forests may be classified as Class I and may be required to undergo far stricter regulatory procedures in order to be approved. The major emission sources existing or presently approved by the Texas Air Control Board are summarized in Table 23.

Thus, barring the possible restrictions posed by the above, it should be possible to have a wide choice is choosing sites for UCG facilities. The siting considerations will then become specialized and site-specific with the plant design and geological considerations receiving primary emphasis. Existing water quality and/or site restoration probably will become limiting factors from an environmental point of view. Some of the lesser areas of concern are impacts on land usage, socioeconomic impacts, impacts on aesthetic values,and impacts on archaelogical and historical sites.

Of the four major impacts, all excepting air quality may be considered as site-specific, and will need detailed site surveys.

Summary and Conclusions

(1) From the developmental work already done on UCG, it is clear that the process (as does any gasification process) offers significant advantages with regard to air pollutant emissions over an aboveground lignite burning facility. The quantities of the emissions of all major pollutants are greatly reduced in a UCG plant for the equivalent thermal or power output.

(2) In view of the present environmental situation in the state, large industrial growth is likely to occur away from the highly industrialized regions on the Gulf coast. This, coupled with the legislative directive to use coal as the fuel for all future plants, will cause new industries, particularly that of power generation, to be located at or near the lignite deposits.

(3) The fact that UCG has lower air pollutant emissions is likely to offer this technology two advantages over conventional lignite plants. Depending upon the size of the plant, project implementation may be acceler-

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TABLE 23: NATURE OF THE MAJOR EMISSION SOURCES IN THE POTENTIAL UCG REGIONS (Figure 36)

UCG REGION	TACB Air Quality Control Region	County	Major Location	Nature of Major Emitting Source
1	03	Bastrop	Several	Brick manufacture, kilns, furnaces, concrete mixing
		Burleson	Several	Natural gas processing, timber treating, plastics
		Lee	Several	Crude oil handling, small boiler
		Milam	Several	Coke & agricultural commodities handling
			Rockdale	Lignite-field boiler/power station
				Coal slag crushing, UCG field unit
2	12	Anderson	Slocum	Refinery, boilers
			Tucker	Naphtha reformer
			Several	Bulk solids, liquids handling and misc.
	03	Freestone	Several	Natural gas processing, solids handling/storage
	03	Leon	Jewett	Arc furnaces
	03	Robertson	Hearne	Crude oil refinery
			Bremond	Lignite-fired power plant, lignite handling
			Several	Natural gas sweetening, solids handling
03	12	Panola	Carthage	Gas pipeline compressor station, boilers
			Several	Fertilizer handling/storage, concrete mixing
	12	Rusk	Tatum/ Henderson	Boiler, loading facilities
			Overton	Gas plant
	12	Shelby	Several	Miscellaneous agricultural, incineration, wood, plastics

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TABLE 23: (CONTINUED)

UCG Region	Control Region	County	Major Location	Nature of Major Emitting Source
04	03	Brazos	Bryan	Gas turbine
			Several	Gasoline/hydrocarbon handling solids handling, small boilers
	03	Grimes	Carlos	Lignite handling, lignite fired power station
			Several	Fertilizer and other solids handling
	10	Trinity	Groveton	Resin polymerization
	07	Walker	Huntsville	Gas and oil fired boiler
			Several	Concrete, asphalt mixing, solids handling
05	09	Atascosa	Jourdanton	Lignite-fired power station
			Several	Gas sweetening, flashing - Bulk solids handling
	05	Live Oak	Three Rivers	Petroleum refinery operations
			Georgewest	Miscellaneous
	05	McMullen	Tilden	Natural gas field
			Freer	Rock crushing

ated by simplified regulatory procedures applicable to sources with smaller emissions. In addition, the application of UCG is expected to allow greater regional growth without adverse effects on the environment.

(4) The actual siting of UCG facilities will reguire primary consideration of a number of site-specific technical design and environmental issues. The latter include the major impacts on water quality and possible land subsidence. Air quality will be a secondary concern in site selection.

SUBSIDENCE FROM UNDERGROUND COAL GASIFICATION

The controlled operation of any underground coal gasification plant requires the ability to predict the in situ behavior of the relevant rock strata, which in turn presupposes a knowledge of the mechanical and physical rock properties. Without this ability unforeseen operational and environmental problems may arise. Of particular importance in this context is the ability to predict roof stability and subsidence during and after the productive life of the operation.

Significant fracturing, deformation, or collapse of the rocks surrounding the cavity can affect the overall operation in many ways. As discussed in Section 3, roof collapse can be beneficial by minimizing void space underground. Excessive void space encourages gas phase oxidation of CO to CO_2, which lowers the heating value of the product gas significantly and causes excessive gas outlet temperatures. The ultimate sweep efficiency of the process depends upon the completeness of the roof collapse. Moreover, if the immediate cavity roof is coal, as it may well be early in the development, collapse of this roof will be advantageous in giving a "self-fueling" effect.

On the other hand, extensive fracturing of the surrounding rocks, or collapse of the roof, could cause serious operational and environmental problems. Roof collapse could lead to excessive gas losses and excessive water influx, possibly causing problems of pollution in overlying aquifers. Finally, any deformation or collapse of the roof rock will ultimately be reflected on the surface as subsidence [56].

As the combustion cavity expands, laterally and vertically, roof support will be removed and concentration of the primitive stress field will occur in the surrounding rocks. Eventually the cavity will extend upwards to the overburden material. The high temperatures associated with the reaction will lead to further thermal stresses on the surrounding strata and also may be expected to have a significant influence on the behavioral characteristics of these rocks [57]. In the case of Texas lignite, fracture and collapse are likely to occur relatively early. The overburden throughout much of the Texas lignite occurrence is unconsolidated sand and mud. Mechanical tests on this material have indicated extremely low tensile strength [57].

Any extensive closure of the cavity, whether by collapse or deformation, will induce subsidence on the surface. For any given depth the potential surface subsidence will increase with the areal extent of the cavity, a factor of some significance if high sweep efficiencies are achieved with Texas lignite. Subsidence has been recognized and in some cases has been

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significant for UCG operations in Russia [58].

The field stations with horizontal seams reviewed by Gregg [58] are located at Podmoskovnaya, Schatskaya, and Lisichansk. At the first two stations, subsidence occurred at the surface continuously, delayed a short time after creation of the cavity underground. No catastrophic subsidence occurred, due to the large sand and clay content of the overburden (low strength). The final level of subsidence was 2 meters for a 3 meter seam. However, it was uniform wherever it occurred. At Lisichansk the seams were thinner, and very little subsidence was observed, probably due to the thermally induced swelling and bulking of the roof rock.

In addition, pillars seemed to have a positive effect on reducing subsidence. In the U.S. field tests, where the gasification areas are smaller than in the U.S.S.R., no noticeable subsidence has been observed except for the Hoe Creek III test performed in 1979, where a subsidence bowl 3 m wide by 13.5 m long by 3 m deep developed after gasification was ceased [59]. Rather elaborate instrumentation at the Hanna and Hoe Creek I and II sites detected essentially no surface movement.

Two types of potential subsidence may be identified. The first, and potentially the more damaging, will be where the surface rocks are fractured by the subsidence, leading to a large scale discontinuity of the roof rock. This would occur if the caved zone limits reached the surface, and is limited to situations of shallow depth or thick seam extraction. This is often referred to as "plug" subsidence. Since roof collapse is a prerequisite for the development of any caving, this subsidence also will be limited to wider cavities. In the worst case, a plug of overburden collapses into the cavity with no significant change in rock fabric within the plug. The maximum subsidence would be the same as the extracted thickness, and a step of this height would occur at the edge of the subsidence area. In a more realistic situation where some bulking occurs, the surface subsidence, and the discontinuity, would be substantially reduced, though the effects on any installations at or near the discontinuity could still be serious.

For deeper cavities, or where substantial overburden fracturing does not occur, a continuous subsidence bowl may be predicted. This is often called "bending" or "bulking" subsidence, and is characterized by an arching of the fractured zone above the cavity. Some indication of possible subsidence in this case may be obtained by treating the overburden as an elastic continuum. Though this assumption is open to question, it is useful in determining the orders of magnitude of likely subsidence. Thompson et al. [60] have analyzed the extent of subsidence for two particular cases of partial cavity closure calculated numerically using a two-dimensional finite-element code. These results are based on laboratory values for the elastic properties of the overburden and are shown in Figure 39(a) and (b).

In this example rather wide and shallow cavities were assumed. The assumptions used in these figures are thus conservative, namely a 100-foot (30 m) half-width of the cavity and a shallow seam. As discussed in Section 6, a 25-foot (7.5 m) half-width might be more realistic, which would cause less surface subsidence. More precise prediction of subsidence will depend

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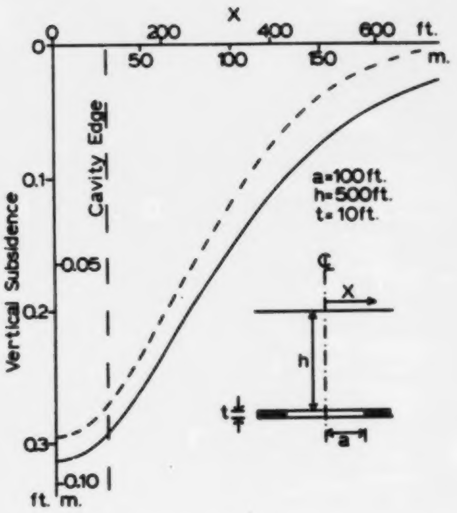

Figure 39(a)

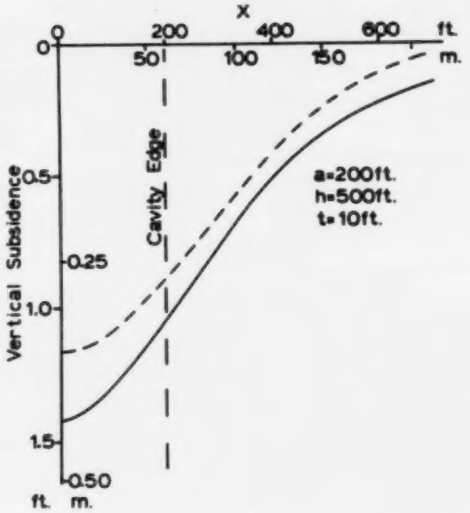

Figure 39(b)

Figure 39. Predicted elastic vertical subsidence [60]

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upon a more realistic model of the gross strata movement and on the development of dried or fractured roof material including local effects of thermal stressing. There is still a wide gap between theoretical predictions and actually observed subsidence phenomena.

An assessment of environmental impact will depend upon the specific site of any future gasification operation and the corresponding rock properties. However, it is clear that the potential for surface damage exists from vertical movement, from tilt on the flanks of the subsidence bowl, and from horizontal tensile strain on the edges of the area. If discontinuous subsidence occurs, the potential for surface damage will be even higher.

Field Design Modifications for Subsidence

As discussed by Gregg and Edgar [2], the basic field design (well layout) can be modified for thick or steeply dipping seams. However, the primary reason for such a change is to protect well casing from excessive shear forces. Gregg [58] has discussed a modified gasification pattern developed in the Soviet Union to reduce subsidence. Tradeoffs between the original and alternative methods occurred in gas leakage, flow resistance, flow control, gas quality, and resource recovery. The normal method, shown in Figure 40(a), involved sequential stepping of the injection wells from row 2 to 3 to 4, while the production hole moved from row 3 to 4 to 5. The dotted line in this figure shows the expected sweep pattern of the gasification front. Gradual (bending) subsidence is expected in this type of pattern.

Figure 40(b) shows the alternate method for gasification. Gasification takes place by injecting into row 2 and producing in row 1. Once the front reaches row 1, injection is initiated in row 3 while production is in row 2. The very different cavity shapes resulting from this pattern are shown in Figure 40(b). The sweep efficiency and thus the degree of caving will be lower for this method than in the first method discussed above. Therefore the differential cost of gasification vs. the imputed cost of environmental damage would have to be evaluated in determining the specific method to be used.

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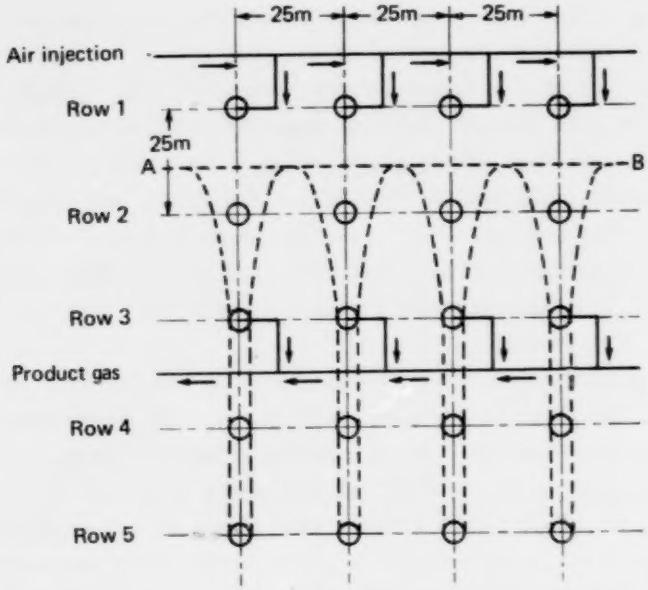
25m
25m
25m
Air injection
Row 1
25m
A
B
Row 2
Row 3
Product gas
Row 4
Row 5

Figure 40(a). Forward gasification in a typical pattern for horizontal coal seams [58]

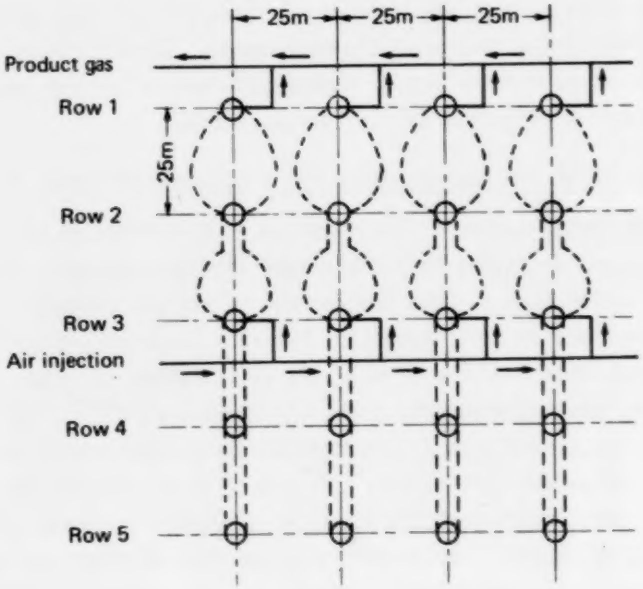
25m
25m
25m
Product gas
Row 1
25m
Row 2
Row 3
Air injection
Row 4
Row 5

Figure 40(b). Reversed gasification in a typical pattern for horizontal coal seams

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Section 8

SUBSURFACE POLLUTANT TRANSPORT AND MIGRATION

DESCRIPTION OF PROBLEM

The description of subsurface pollutant transport and migration after UCG requires a knowledge of the natural groundwater flow field as well as an understanding of dispersive and diffusive processes as the contaminant is carried along with the groundwater flow. Superposed on the convective and dispersive transport are the physicochemical processes such as ion exchange, adsorption, and precipitation. The combination of these various processes forms the complex problem of convective-dispersive transport of a chemically reactive species.

Regional Groundwater Flow in Texas

The fundamental mode of transport is convection by the groundwater flow field. Thus a first step in analyzing the fate of a pollutant is a detailed study of a regional groundwater flow. Principles of regional groundwater flow have been discussed by Toth ([61], [62], [63]), and Freeze and Witherspoon ([64], [65], [66]). A basic conclusion of regional flow theory is that the flow distribution is controlled to a large extent by regional topography. High elevations act as recharge sites while low elevations act as sites of groundwater discharge. In regions of subtle relief regional groundwater flow systems of large extent may exist. But where extensive relief exists, only local flow systems are found. Cross-formational flow is a common occurrence. This notion that extensive aquifers act as major conduits only over regions limited by regional topography has often been neglected in studies of large scale flow systems. The regional flow provides a general picture of the direction of transport as well as boundary conditions for subsequent detailed analysis of local groundwater flow fields.

One study of special interest is that of Fogg and Kreitler [21]. They investigated the hydrogeology of Eocene aquifers in the East Texas Basin, an area which includes possible sites for in situ gasification of lignite. Fogg and Kreitler concluded that the flow direction in this region is controlled more by regional topography than by the geology. This is at first surprising because the topography is subtle (compared with the regions of Alberta with which Toth [63] was concerned). If this proves to be the general case for other regions containing gasification sites, then the problem of site selection is reduced to including only those sites which are located on topographic highs. Any contaminant which did move with the regional flow would have a longer path before being introduced into the biosphere (See

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also Section 5).

Available Mathematical Tools for Transport Predictions

Mathematically, the problem of contaminant transport of a chemically reactive species translates into a coupled system of equations

$$\nabla \cdot \underline{\underline{K}} \cdot \nabla h = S_s \frac{\partial h}{\partial t} \tag{1}$$

$$\underline{v} = -\frac{1}{n} \underline{\underline{K}} \cdot \nabla h \tag{2}$$

$$\nabla \cdot \underline{\underline{D}} \cdot \nabla c - \nabla \cdot (\underline{v}c) + \frac{I(c)}{n} = \frac{\partial c}{\partial t} \tag{3}$$

Equation (1) states the conditions of conservation of volume of water in the total volume of void space plus solid matrix. $\underline{\underline{K}}$ is the hydraulic conductivity tensor, h is the hydraulic head, S_s is the specific storage and ∇ is the three-dimensional divergence operator. Equation (2) is Darcy's law stating the momentum equation for flow conditions where inertial effects are unimportant; n is the effective porosity of the porous media. Equation (3) states the conditions of conservation of mass of a particular species. $\underline{\underline{D}}$ is the hydrodynamic dispersion tensor including both the effects of mechanical dispersion and diffusion; c is the chemical species mass concentration (mass of species/unit fluid volume). I(c) is the rate of increase of species mass per unit volume (total volume, not void volume). It incorporates such effects as ion exchange and adsorption processes as well as release of species from ineffective storage.

With major simplifications the system (1) - (3) may be reduced to a form amenable to treatment by analytical methods. For many analytical treatments the major assumptions are that the problem is one-dimensional and that the flow field is steady, i.e., the time derivative in equation (1) is equal to zero (the time derivative in equation (3) is not equal to zero since the contaminant can still move around in a steady flow field). Then for a one-dimensional problem equation (1) becomes

$$\frac{d}{dx}\left(K \frac{dh}{dx}\right) = 0 \qquad \text{(K is a scalar)} \tag{4}$$

or

$$K \frac{dh}{dx} = \text{constant} \tag{5}$$

For a one-dimensional problem equation (2) is

$$v = -\frac{1}{n} K \frac{dh}{dx} \tag{6}$$

so as long as the porosity is uniform, the flow velocity in a one-dimensional steady problem is constant. For this simple problem equations (1) and (2) are thus eliminated and equation (3) becomes

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$$c(x, 0) = 0,\ x > 0$$

$$c(0, t) = c_0,\ t > 0$$

$$c(\infty, t) = 0,\ t \geq 0$$

An approximate solution which is valid for all but very small x and t is

$$\frac{c}{c_0}(x,t) = \frac{1}{2}\,\mathrm{erfc}\,\frac{x - \frac{v}{B}t}{\sqrt{4\frac{D}{B}t}} \qquad (13)$$

where erfc is the complementary error function. The contour $\frac{c}{c_0} = 0.5$ travels so that it always satisfies $x - \frac{v}{B}t = 0$ (erfc [0]=1). Thus for flow without sorption, x = vt, while with sorption, $x = \frac{v}{B}t$ for the $\frac{c}{c_0} = 0.5$ contour. Since B>1, this shows that the front moves at a slower rate with sorption. The solution given is a normal probability density function. The spacial variance of the distribution is $\sigma^2 = 2\frac{D}{B}t$ with sorption. In other words, sorption causes the front to move slower and be steeper. This poses a special problem for numerical methods which do not accurately represent a steep concentration front.

Other analytical solutions have been used by Elder and Dagan [68], Holly et al. [69], and Cameron and Klute [70]. Holly et al. [69] described a one-dimensional analytical solution to the transport model with a radioactive decay term. Two approximate solutions were given for dispersion normal to flow. One solution is based on the assumption that longitudinal and lateral dispersion act independently of each other. The value of the concentration is the product of the one-dimensional transport solution and the lateral dispersion solution. This solution puts the source into square horizontal sections. The second approximation divides the source into a finite number of cells and each cell moves from the source to a new (x,y) location. This method does not provide for a continuous release of waste, but can only be used for the release of a slug.

Henry [71] used an analytical solution to solve the transport equation in two dimensions. Adsorption was not treated individually, but was treated as a reduction in velocity. This solution involved an approximate solution to the error function. Cameron and Klute [70] solved the transport equation analytically assuming that chemical transport through soil was a combined kinetic/equilibrium model. This method yielded a one-dimensional solution and incorporated adsorption, desorption, and equilibrium constants. The authors have obtained good results in fitting their model to existing data. Homsy [72] presented a number of analytical solutions to the transport equation for a uniform flow field with different sets of boundary conditions. He considered a two dimensional domain with equilibrium adsorption satisfying a linear isotherm. While the solutions are of some interest, the restriction to a linear isotherm and neglecting leakage from adjacent units limits their applicability. Lyckowski, et al. [73] also presented a number of analytical solutions to the transport equation for different boundary conditions. Their work is of special interest in that they discussed the fundamentals of dispersion and diffusion, as well as the use of tracers in laboratory and field tests.

$$\frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) - v\frac{\partial c}{\partial x} + \frac{I(c)}{n} = \frac{\partial c}{\partial t} \qquad (7)$$

which may be integrated after appropriate phenomenological assumptions are made concerning dispersion and reactions.

In transport of pollutants from UCG, special emphasis is placed on sorption phenomena. The reaction term $I(c)/n$ may be interpreted for sorption phenomena as follows. Let q be the mass of the sorbed phase pollutant per mass of the solid matrix and ρ be the bulk density of the porous media (mass of solids per unit volume). Then $\rho q/n$ is the mass of the sorbed phase of pollutant per volume of voids. If the mass of the pollutant in solution is increasing, then the mass of the sorbed phase must be decreasing. Thus since ρ and n are constant,

$$\frac{I(c)}{n} = \frac{\rho}{n}\,\frac{\partial q}{\partial t} \qquad (8)$$

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To go further one needs the adsorption isotherm which may be determined from laboratory experiments. The isotherm is a plot of the sorbed phase pollutant q versus the concentration of pollutant in solution c and the slope of the isotherm is called the distribution coefficient K_d (see Pickens and Lennox [67]).

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$$K_d = \frac{dq}{dc}$$

In terms of the distribution coefficient one may write

$$\frac{I(c)}{n} = -\frac{\rho}{n}\,\frac{dq}{dc}\,\frac{\partial c}{\partial t} = -\frac{\rho}{n}\,K_d\,\frac{\partial c}{\partial t} \qquad (9)$$

and the transport equation becomes

$$\frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) - v\frac{\partial c}{\partial x} - \frac{\rho}{n}K_d\frac{\partial c}{\partial t} = \frac{\partial c}{\partial t} \qquad (10)$$

or

$$\frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) - v\frac{\partial c}{\partial x} = B\frac{\partial c}{\partial t} \qquad (11)$$

where $B = (1 + \frac{\rho}{n}K_d)$ is called the retardation factor.

To further highlight the influence of sorption one may consider the simple case of steady one-dimensional flow with a linear isotherm ($q=\alpha c$ so $K_d = \frac{dq}{dc} = \alpha$). Now $B = (1+\frac{\rho}{n}\alpha)$ and equation 11 becomes

$$\frac{\partial c}{\partial t} = \frac{D}{B}\,\frac{\partial^2 c}{\partial x^2} - \frac{v}{B}\,\frac{\partial c}{\partial x} \qquad (12)$$

with boundary conditions corresponding to an initial step front,

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Campbell and Washington [37] have determined that the boundary condition which most mearly matches the concentration in the burn cavity after in situ gasification of lignite is a linear variation of concentration with time. The appropriate boundary condition is

$$c(o, t) = (c_0 - At), \quad 0>t>t'$$

$$c(o,t) = 0, \quad t>t'$$

where A is the rate of decrease of the source concentration and t' is the time at which the source concentration becomes zero, i.e., $t'=c_0/A$. The work of Campbell and Washington [37] is in error in that they used the retardation factor $B = (1+ (\frac{1-n}{n})\ K_d)$ wherein they should have used $B = (1+ \frac{\rho}{n} K_d)$.

Humenick and Novak [42] have carried out a parametric analysis of pollution migration following in situ gasification of lignite using the analytical solution of Holly et al. [69]. A number of assumptions are inherent in their analysis. These are

(1) One-dimensional flow and dispersion. This is a particularly good assumption at high velocities, but when groundwater velocities are five m/yr or less, the lateral dispersion gains greater importance.

(2) The distribution coefficient is constant. Both Campbell and Washington [37] and Humenick and Mattox [74] have shown that the distribution coefficient is a function of the solute concentration.

(3) Source concentration changes at a constant rate with time.

(4) Solution of the complementary error function is an approximate solution.

(5) The program will only deal with one contaminant; so, complex multi-component interactions will not be considered.

(6) The groundwater basin has distinct boundaries. Outside of these boundaries there is a no flow condition.

(7) The porous medium is homogeneous and isotropic.

(8) The density, viscosity, porosity, and groundwater velocity are constant over the entire system.

(9) The sorbed and solution phases of the contaminant present are in equilibrium.

Among their conclusions, Humenick and Novak [42] stated that the parameters with the greatest effect on peak concentrations are the initial source concentration and the groundwater flow velocity. The ideal site characteristics for minimizing groundwater pollution would be a low initial source concentration, a low groundwater velocity, a low porosity and a high distribution coefficient. As a practical matter only identifying sites with low groundwater velocities would be effective at this time.

Numerical Solutions--

While analytical solutions of the system (1) to (3) are possible under idealized conditions (such as discussed above), most realistic conditions and field problems require use of the more general framework of numerical methods. Numerical methods reduce the system of partial differential

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equations to an approximating system of algebraic equations which are readily programmed and solved on the computer. Two classes of numerical methods have found general applicability. These are the finite difference methods and the finite element methods. Application of the former to subsurface hydrology has been reviewed by Remson et al. [75] while finite element method applications have been reviewed by Pinder and Gray [76], with particular emphasis on contaminant transport problems.

Within the realm of finite difference methods Pinder and Bredehoeft [77] and Bredehoeft and Pinder [78] applied the alternating direction implicit scheme to two- and three-dimensional problems, respectively. Freeze [79] used the three-dimensional line successive over-relaxation technique. More recently Konikow and Bredehoeft [80] have proposed a model which simulates the flow using the alternating direction implicit finite difference scheme and uses the method of characteristics to solve the contaminant transport equation. The Texas Department of Water Resources uses an iterative alternating direction implicit scheme [81], [82] fashioned after an earlier computer code developed by Prickett and Lonnquist [83].

Finite element methods have found considerable application in recent years. Pinder and Frind [84] proposed a Galerkin method for aquifer flow analysis while Pinder [85] extended the approach to include contaminant transport. Van Genuchten, Pinder, and Frind [86] have used isoparametric hermitian elements to solve the transport problem. An integrated finite difference method which is similar to the finite element method has been suggested by Narashimhan and Witherspoon [87].

Comparison of finite difference and finite element methods have been made by Pinder and Gray [88], Gray and Pinder [89], [90], Narashimhan and Witherspoon [87], as well as many others. Pinder and Gray [88] and Gray and Pinder [90] show that while the finite difference method approximates a differential equation at a point, the finite element method may be interpreted as spacial averages of standard finite difference equations written at a node. Gray and Pinder [89] have shown that the finite element method is superior to the finite difference method in propagating a sharp concentration front. This may be an important consideration in modeling pollutant migration after UCG because both numerical techniques cause overshoot and under-shoot at the front and may result in fictitious negative concentrations which will interfere with the computation of chemical reactions. Narashimhan and Witherspoon [87] suggest that both numerical techniques have advantages depending on the class of problems to be solved. They found that the finite element method is well suited to handle general tensorial problems such as hydraulic conductivity and dispersion and can approximate rapid variations of hydraulic head with greater accuracy than the finite difference method. The finite difference method has the advantage of greater simplicity and easily defined local stability conditions.

While use of numerical models (three-dimensional models in particular) require large amounts of computer time, their cost represents a relatively small expenditure in the total cost of any field study. Beyond their actual predictive capability, the models are beneficial in that the organization of field data required for these models provides great insight into

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actual field behavior.

Model Limitations

Equations (1) and (3) state the basic physical requirements of conservation of mass. The general formulation of these models is dictated by physics. Equation (2), on the other hand, is an empirical statement generalizing the experimental results of Darcy. Many subsequent investigators have verified equation(2) and pointed out its basic limitations, namely low Reynolds number flows where inertial effects are unimportant (e.g., Hubbert [91], Scheidegger [92], Bear [93], or Fried [94]).

For equation (3) a number of models have been suggested relating the dispersion tensor to the velocity field. A generally accepted model for isotropic dispersion is that of Scheidegger [95] which is based on the work of de Jong [96] and Bear [97]:

$$\underline{\underline{D}} \equiv D_{ij} = a_T v\delta_{ij} + (a_L - a_T)\frac{v_i v_j}{v} + D_d\tau$$

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where a_T and a_L are the dispersivities in the transverse and longitudinal directions respectively, δ_{ij} is the Kronecker unit tensor, v_i = components of $\underline{v}$, $v = |\underline{v}|$, D_d is the coefficient of diffusion and τ is the tortuosity of the porous media. In its one-dimensional form this gives

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$$\underline{\underline{D}} \equiv D = a_L v\delta_{ij} + (a_L - a_T)\frac{v_i v_j}{v} + D_d\tau$$

stating that dispersion is a linear function of the velocity. Laboratory experimental results suggest an exponent somewhat greater than unity at higher Reynolds numbers (See Harleman and Rumer [98]). Cherry et al. [99] have discussed the difference between laboratory and field values of the longitudinal dispersivity a_L. Laboratory experiments give values of a_L on the order of 10^{-2} to 1 centimeter while values matched from field data suggest that a_L is on the order of 10^3 to 10^4 centimeters. Thus frequently laboratory and field values can differ by a factor of about 10^5. It is apparent that dispersion typical of field problems is on a scale much larger than dispersion typical of laboratory studies. In effect, the heterogeneous hydraulic conductivity field disturbs the macroscopic flow in much the same way as the presence of sand grains disturbs the microscopic flow.

For modeling transport of a contaminant away from the burn cavity (Figure 16) and for field contaminant transport problems in general, the discrepancy between laboratory and field scale flows is even more severe than having the dispersivity differ by a few orders of magnitude. The basis of the dispersion type of model is that the contaminant has moved a sufficient distance so that it has undergone enough "random jumps" for Fickian type mixing to have taken place (Bear [93], Bird et al. [100]). On a very small scale (molecular) this mixing corresponds to classical diffusion. Mixing also occurs because of heterogeneities on the scale of the individual grains or pore lengths due to the interweaving of the pore paths. It is this scale of mixing which is measured in the laboratory and which is characterized by a low dispersivity (10^{-2} to 1 centimeter). On a still larger scale one finds mixing caused by the presence of heterogeneities in the hydraulic

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conductivity field of the porous media. A study of depositional processes and individual deposits shows that these heterogeneities can and do occur simultaneously on many different scales. Reineck and Singh [101] mentioned that individual sedimentary beds vary in thickness from a few millimeters to tens of meters but they are usually measured in centimeters or multiples of centimeters. The alluvial point bar, channel bar, channel fill, channel lag, levee, crevasse splay, flood basin, and marsh deposits all show various structures varying in size up to tens or hundreds of meters. Regional characteristics vary on a scale of hundreds of meters to kilometers. The major point of interest is that heterogeneities occur on all scales of size and that the larger the scale of the heterogeneity, the larger will be the value of the dispersivity which characterizes Fickian mixing caused by this scale of heterogeneity (assuming the same linear model). Similarly, the farther the contaminant moves, the larger will be the biggest scale of heterogeneity to appear as Fickian mixing. Scales of heterogeneities which are larger than this biggest Fickian-scale heterogeneity must be modeled explicitly as a heterogeneous parameter field. The transport associated with these larger scales must appear as convective transport.

For example, consider the depositional system associated with an alluvial piedmont slope. Streams which carry the sediment load change their course by lateral migration and by overflowing their banks, carving new channels and abandoning the old ones (downstream). Consequently relatively uniform deposition is found throughout the fan or piedmont slope. The coarser channel deposits downstream on an abandoned channel are left to be covered by finer overbank deposits from flooding of neighboring channels. Thus, discontinuous sand and gravel lenses may be formed. This system is characterized by extreme heterogeneities in the conductivity field (between fine silt and sand) up to lengths of tens of meters. Milder heterogeneities (between silts) are also found up to lengths of a kilometer or so corresponding to a fining of the deposits as one moves away from the center of the meander belt. In this system flow between wells several hundred meters apart could be modeled by a low, fairly uniform conductivity field with a fairly high dispersivity. On the other hand, if flow between wells located 10 to 20 meters apart is the setting, then the location of a sand lens would greatly disturb the flow and any model attempting uniform flow with dispersion would not fit the reality. The heterogeneity must be modeled explicitly in the hydraulic conductivity field. Of course, a dilemma immediately arises because the exact location and extent of the lens is unknown.

The strong influence of heterogeneities on flow in real aquifers represents a major limitation to applying models for predicting actual field performance. Analytical and numerical models are excellent for predicting system performance under given physical and chemical conditions but determination of the physical and chemical conditions of a particular field site at a sufficient scale of resolution for use in modeling is extremely difficult. While research is progressing in this area of solving the "inverse problem", the results to date limit the application of modeling to hypothetical field sites. Because the flow will exhibit fingering caused by the presence of heterogeneous hydraulic conductivity fields, interpretation of field monitoring data may be extremely difficult.

Another model limitation arises when one considers the distinction

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between the original or primary void space and the secondary or fractured void space. The original void space has a much greater capacity for water storage than the secondary void space but the fractured voids have a much higher hydraulic conductivity than the original voids. The net effect is that a pressure wave is transmitted quickly through the secondary voids while delayed storage release occurs from the primary voids in response to the change in head in neighboring secondary voids. Such a model has been presented by Barenblatt et al. [102]. Recently Streltsova-Adams [103] reviewed the topic of flow in fractured porous media. The problem of flow in fractured porous media is of interest in underground gasification of lignite because the lignite itself is known to be highly fractured. More importantly, as far as pollutant migration is concerned, the overlying beds may become fractured in the stress field caused by the burn cavity. The combination of fracturing of overlying deposits and roof collapse may result in communication between aquifer units which originally were separated by confining aquitards.

UCG SITE HYDROLOGY IN TEXAS

In this section the hydraulic data from Texas field tests of UCG are reviewed. These data have been obtained from field pumping tests and from laboratory tests of core samples. The data reported here have largely been obtained from applications to the Railroad Commission of the State of Texas of mining permits.

In 1978 Texas A & M University conducted a field test at a site near its campus (Easterwood test site) in the Eocene Yegua Formation. The lignite was overlain by about 1/2 meter of claystone followed by about 7 meters of fine to medium grained sand. The mud and lignite are interpreted to be shallow lake deposits while the sand consists of stream deposits. The 1 1/2 meter thick lignite deposit was tested using Jacob's method of pumped well analysis. The conductivity was found to be 1.1 m/d (meters/day) while transmissivity was 3 to 10 m^2/d. A storage coefficient of 10^{-4} to 10^{-5} was found. An attempt was made to determine whether the mud made an effective seal between the lignite and the sand, but the test, which consisted of pumping at a rate of about 70 m^3/d for 10 hours, is not sufficient for estimating conductivity when the observation well in the sand is 25 meters away from the pumping well in the lignite. In attempting to link the wells, severe problems developed with override, where the flow went through the mud at the injection well and into the overlying sand. This test showed that such a thin clay overburden is not sufficient for running field tests. Preliminary tests showed that the natural hydraulic gradient within the lignite was less than 0.001.

Within the Calvert Bluff Formation of the Wilcox Group, field tests have been conducted by Basic Resources, Inc. (Tennessee Colony Site and Big Brown Site, Figures 6, 15, and 19) and Texas A & M (Alcoa site, Figures 6 and 15). The Calvert Bluff Formation consists of interbedded sand and mud. Most of the lignite was deposited as fluvial peats in fresh-water swamps and marshes in broad flood basins between stabilized meanderbelts and associated levee ridges. These deposits are generally elongated parallel to paleochannel complexes. Some sections of the Calvert Bluff produce water but generally it is a poor producer. The Calvert Bluff Formation is

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underlain by the Simsboro Formation of the Wilcox Group. The Simsboro Formation is mostly sand with some mud; it is a prolific water producer. Overlying the Calvert Bluff Formation is the Carrizo Sand of the Claiborne Group, which is an excellent water producer.

The Texas A & M Alcoa site shows a 5 meter lignite bed overlain by 15 meters of silty-clay and underlain by 18 meters of clay. The permeabilities of the clay and silty-clay are low, though the values reported in the application to the Railroad Commission of Texas, which were less than that of unfractured metamorphic or igneous rock or shale, were undoubtable in error.

The Basic Resources, Inc. Tennessee Colony Site show a 2 to 3 meter thick lignite deposit overlain by a 23 to 30 meter thick clay and silty-clay. Above this confining layer is the Carrizo Sand. Below the lignite is a 5 to 7 meter clay and silty-clay layer followed by a 4 to 5 meter thick silt. The Simsboro Formation is located about 120 meters below the lignite. The hydraulic conductivity of the lignite varies from 0.03 m/d (slug test in the field) to 0.045 m/d (laboratory test). With a measured porosity of 0.3 and a measured hydraulic gradient of 0.002 and assuming a conductivity of 0.4 m/d, the natural rate of water movement is (0.04) (0.002) (365)/(0.3) = 0.1 meter/yr. By way of contrast, the Carrizo has a natural hydraulic gradient of 0.0026, a porosity of 0.35 and a hydraulic conductivity of 8.5 m/d, implying a rate of water movement of 23 meters/year. At the test site the piezometric head in the Carrizo is 0.3 meters below that in the lignite. With a measured hydraulic conductivity in the overlying clay and silty-clay of 10^{-6} m/d and a porosity of 0.3, the rate of water movement between the lignite and the Carrizo (about 25 meters above) is $(10^{-6})(0.3/25)(365)/(0.3) = 1.5 \times 10^{-5}$ m/yr. A point of interest is that the horizontal hydraulic gradient varies from 0.002 in the lignite to 0.0026 in the Carrizo while the vertical hydraulic gradient between the lignite and the Carrizo is 0.3/25 = 0.0012, an order of magnitude greater. Thus for large scale in situ gasification sites, development of fractures in the overlying clay and silty-clay unit will greatly increase vertical hydraulic conductivity. Such fractures would open up an avenue to flow from the lignite, through the gasification cavity, and up into the Carrizo aquifer.

The Texas Utilities Company Big Brown Site shows a lignite deposit between 2 1/2 and 3 meters thick. Overlying the lignite is 2 to 5 meters of clay followed by 3 to 6 meters of interbedded silty sand, silt and clay which forms a water bearing unit. Below the lignite is a clay unit which varies in thickness from less than one meter to 3 meters. Below this clay is a 2 to 5 meter unit consisting of silty sand with some silty-clay layers. In all there are 5 water bearing units at the test site. The uppermost of these, a sand with silty clay which is about 40 meters above the lignite to be gasified, is the most prolific producer. Its horizontal hydraulic conductivity varies from 0.015 to 2.6 m/d (transmissivity varies from 0.07 to 16 m^2/d). The measured hydraulic gradient is 4×10^{-3} so with a porosity of 0.35 the rate of water movement under natural conditions varies from 0.06 to 11 meters/year. In descending order, the range of hydraulic conductivities of each unit and hydraulic gradients of the water bearing units only are shown in Table 24 below. Thus, the maximum rate of horizontal movement

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near the lignite is less than 2 m/year while the rate of movement within the lignite varies from 0.03 to 0.5 m/year. Pumped-well tests reported by Itz and Oliver [104] suggest that the water bearing units near the lignite (including the lignite itself) are "leaky" and that the natural direction of movement is toward the lignite from both above and below. Data from laboratory tests in the application to the Railroad Commission showed that the horizontal hydraulic conductivity exceeded the vertical hydraulic conductivity by a ratio of from 4 to 40 times. Thus, strong local anisotropy exists.

TABLE 24: HYDRAULIC CONDUCTIVITIES AND HYDRAULIC GRADIENTS OF UNITS SURROUNDING BIG BROWN LIGNITE

	hydraulic conductivity (m/d)	hydraulic gradient
(1) silty sand above lignite	0.013-1.2	0.0013
(2) clay above lignite	0.0006	-
(3) lignite	0.012-0.2	0.0018
(4) clay below lignite	0.001	-
(5) sand below lignite	0.011-0.16	0.0017

CONCLUSIONS AND RECOMMENDATIONS

Preliminary information from laboratory and field tests show that most contaminants of interest are absorbed near the gasification site, either in the lignite or the overburden, and do not move very far away from the cavity. Field data also show that because of the small hydraulic gradients and conductivities, the rates of movement are very small, typically a meter per year or less. This low rate of movement may explain why some pollutants are not observed in observation wells which are close to the burn cavities. Also, at these low velocities diffusion may be as important as dispersion.

The general mathematical models used for prediction and simulation of flow and transport are deemed to be adequate. Analytical models reflect the behavior of idealized systems and are useful for highlighting the influence of different processes and parameters. But realistic problems require the use of numerical models with their much greater flexibility. The science and art of numerical modeling is highly developed, and there are few physical problems which defy analysis. The limitation of numerical models lies in the difficulty in finding the appropriate parameter values to use in the models. This "inverse problem" of finding the parameter values is being intensively researched at present and remains a pressing problem for the future. No completely satisfactory procedures are available at present.

The trade-off between the convective and dispersive terms in a mathematical model with the scales of heterogeneities remains a fundamental problem in the analysis of field transport problems. Use of very advanced chemical models will offer limited rewards in field simulations if the hydraulics is poorly represented. An approach to this problem which shows some

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promise is conditional simulation. One uses the regular mathematical models but treats the parameter field as a realization of a stochastic process. The parameter field has the appropriate statistical structure for the depositional system as well as the deterministic structure which is known from actual field tests (the parameter field takes on the measured values at the measurement points). By examining a number of simulations one obtains an estimate of the expected or mean field behavior as well as an estimate of the extensive departures from the expected behavior-all consistent with known information. This approach should be investigated in the future.

Fractures within the porous media present a number of problems. There is no generally accepted model of the hydraulics of flow in fractured media. Also, in the problem of in situ gasification of lignite, development of fractures in the overburden presents an avenue for increased cross-formational flow between neighboring water bearing units. This problem of the interaction of overburden fractures with the regional groundwater flow should be investigated in the future.

Also, since it is evident that contamination from the gasification site will not be immediate, one must consider changes in water use patterns in the future and how contamination might influence these patterns. Of special interest is the increase in hydraulic gradients and the corresponding increase in the rate of contaminant transport.

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Section 9

RESTORATION AND WATER POLLUTION CONTROL OF UCG SITES

Previous sections have discussed the types of pollutants that can be released to groundwaters from UCG operations. This section discusses what the long and short term impacts to groundwaters might be, what types of regulations might be proposed for restoration requirements, what control technologies might apply to abate surface and subsurface water pollution, and how sites may be chosen to minimize environmental pollution.

ESTIMATION OF SHORT AND LONG TERM IMPACTS TO GROUNDWATER

The short term impact of UCG on groundwaters can be evaluated, using data obtained from field and laboratory studies on gasification of subbituminous coal and Texas lignite (see Section 7). Although there are some differences between the two coals, the data are qualitatively similar. In both cases it was found that a wide array of organics condensed in the surroundings and then were released to groundwaters according to their solubilities. Besides the condensible organics, ammonia, hydrogen sulfide, cyanide, and other gases are also absorbed from the gas products. Resulting concentrations of these contaminants can be high, as seen in the previous tables. Inorganic species are also initially present in high concentrations in the groundwater due to ash leaching. These contaminants are mostly calcium, sulfate, and bicarbonate ions, but also a wide array of other species potentially more harmful are also released. These contaminants include boron, selenium, arsenic, and other metals.

The above data indicate clearly that the short term impacts would be undesirable if they persisted. However, available data from two small field studies (one in Texas and one in Wyoming) have shown significant reductions in pollutant concentrations with time. No man-initiated restoration techniques were applied at these sites. Thus, natural cleansing processes must account for the water quality improvements.

Although the field data are encouraging, it must be realized that the field tests were of a relatively small scale as compared to a commercial operation. Further, there has not been a specific and definitive study of a field operation in Texas where extensive water quality information was a primary objective. For comparison, the Wyoming site (Hoe Creek) has been and is being studied in some detail. Again, results are encouraging, but the water is not as yet restored.

At this time it is not possible to explain completely the improvement

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in water quality with time or to predict the long term fate of pollutants released to groundwater. Clearly, the mechanisms are complex with many potential physical, chemical, and biological processes that could be important. With the exception of some study of the adsorptive properties of organic compounds on surrounding strata, the important mechanisms affecting long term fate of pollutants are not known. There has been no long term field test from which to obtain real time environmental data, and none of the U.S. tests have been on a commercial scale.

RESTORATION OF GROUNDWATER QUALITY

Previous sections have discussed the types of contaminants which can be released to groundwaters and degrade water quality (at least initially). Because of the potential pollution problems, the following questions must be addressed in a rational and consistent way:

(1) Is restoration of groundwater quality needed?
(2) If so, to what level must the quality be restored?
(3) How shall restoration be accomplished?

At the present time there is no clear policy specified in the existing regulations (RCRA, SMCRA). Hence, it is appropriate in this report to discuss the above questions prior to finalization of regulations.

Is Restoration Needed?

Although local contamination of groundwater can occur, in some cases restoration may not be necessary. It can be argued that regulations on restoration should be flexible (decided on an individual case basis) rather than universally requiring all groundwater to be restored. The following questions should be addressed for a specific site:

(1) Is the water quality of an aquifer high?
(2) Is the aquifer productive?
(3) Is the aquifer now or potentially a usable souce of water?

An aquifer might be declared exempt from restoration (or minimal restoration efforts would be required) if it failed one or more of the above conditions.

Several scenarios can be proposed to illustrate when restoration could or could not be required. For example, if roof collapse occurred and an overlying aquifer became contaminated, required restoration may be extensive if the overlying aquifer was a major water supply as is the case for the Carrizo in Texas. Another case could be when the water quality is quite good within the coal seam, but the aquifer is very non-productive (low transmissivity) or the local groundwater flow velocities are very low (low hydraulic conductivity). In this case perhaps only minimal restoration would be required. A third situation would be where there is no groundwater in the coal seam. Other situations could exist and may be unique. Hence individual restoration criteria for each UCG site may need to be established.

What Level of Restoration is Needed?

The range of restoration requirements could lie between no restoration to restoration to original baseline water quality. Perhaps either extreme is impractical for a large-scale UCG operation. In general, the inorganic contaminants generated by ash leaching and some of the lighter condensed organics will migrate at or near the groundwater velocity. Thus, only if there is no groundwater flow could restoration possibly be obviated.

"Minimal" restoration could be defined as a strategy where the burn cavity is pumped until total dissolved solids was reduced to a level near baseline. Minimal restoration might be a practical approach if future laboratory and modeling efforts can show that natural processes such as adsorption, precipitation, and biological degradation can cleanse the aquifer in a reasonable time.

Complete restoration of all water quality parameters appears to be an impossible task based on available data. For example, if a large amount of pumping of the burn cavity was used to remove contaminants from the aquifer, the inflowing water from the surroundings would probably have a different water composition than was there during baseline studies [40]. Further, the condensed organics in the periphery around the burn cavity (Figure 16) would continue to be slowly dissolved by the influxing water and remain as a source of organic contaminants for a long time due to their low solubility. The concentrations of dissolved organics would consequently be rather low.

The degree of restoration required probably should be based on a case-by-case evaluation. Actual requirements could be criteria similar to those previously proposed. It is not easy to arrive at quantitative bases to define the restoration goals. Bases that have been used in the past in Texas are:

(1) Restoration shall be equal to or better than drinking water standards.

(2) Restoration shall be to baseline water quality or better.

It is interesting to note that one small UCG site (at Fairfield, Texas) has been declared restored by the Texas Railroad Commission in Texas. Restoration was established to be a return to baseline in water quality parameters and was accomplished without any specific control actions, rather the site was simply monitored for one year. As discussed earlier, natural physical, chemical, and biological processes occur in the underground system which cleanse the water with the passage of time. Dilution or groundwater flow was not considered effective at this site because the mean groundwater velocity was estimated to be less than five feet a year. Data illustrating these changes in water quality have been previously presented in Section 7.

TREATMENT OF CONTAMINATED WATER

There are three concepts which may be considered for treatment of contaminated groundwater from in situ gasification. One concept is to do nothing, which has been discussed previously. A second concept is one of containment. A third concept is one of treatment and/or disposal.

The concept of containment could be applied to a situation where little or no groundwater flow occurs in the coal seam. Here a strategy would be to monitor the periphery of the burn zone to insure that contaminants were not migrating from the contaminated area. Possibly a hydraulic barrier (a line of pumping wells) could effect containment of pollutants. Containment for abandoned shale oil retorts has also been investigated [105]. Groundwater pollution control problems for in situ shale oil retorting are similar to UCG problems although UCG will occur over a much wider area than in situ oil shale retorting. Fox and Persoff [105] have proposed several control technologies for containment, such as a hydraulic bypass around the contaminated zone, placing adsorbent clays within the cavity, and placing a grout curtain around the contaminated zone. Unfortunately, actual cost and effectiveness have not been established because of the absence of field data.

Another concept for control would be pumping the contaminated water from the cavity and surrounding and treating or disposing of the water on the surface. This alternative would be effective for removal of the highly mobile contaminants. These contaminants would be most of the material generated by ash leaching, the lighter, more soluble organics, and most of the ammonia. The material remaining behind would be the more insoluble, less mobile condensed organics around the periphery of the burn zone. Pump out is the accepted method for treating water from in situ uranium leaching sites in Texas.

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Other techniques that could be used for restoration include:

(1) Reliance on natural restoration processes to cleanse the in situ water.

(2) Enhancement of the in situ natural restoration processes.

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It should be pointed out that these techniques are not yet based on established knowledge of practice and require development.

The surface treatment and/or disposal of the contaminated water from UCG has not been studied as yet. However, similar types of waters from in-situ shale oil retorting and above ground coal gasification processes have been studied [105], [106], [107], [108], [109]. The proposed schemes include a wide array of operations such as deep well disposal, evaporation ponds, adsorption on spent ash or activated carbon, biological treatment, gas stripping, ion exchange, reverse osmosis, distillation, solvent extraction, sedimentation, thickening, and filtration. These operations are generally well-known and reliable. However, no full-scale treatment system exists and wastewaters specific to in situ coal gasification have not been analyzed in treatability studies.

Above-Ground Wastewaters

Wastewaters generated above ground arise from gas processing. The principal streams are condensates produced when the hot gas is cooled and other streams which may be generated by the various gas cleaning systems employed. Again, no specific research on the treatment of these streams has been performed for UCG, although some characterization of the condensate has been performed [40] at the University of Texas.

To find guidance in this area, one may refer again to the work in related fields of oil shale retorting and above ground coal conversion. Several processes have been proposed ([104], [105], [106], [107], [108]).

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a few tested at the bench scale. The same unit operations cited above for treatment of in situ contaminated water are proposed for treatment of above ground wastewaters. However, more research is needed on the control technology for these wastewater streams in order to enhance efficiency and reliability.

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Section 10

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

In this Section we summarize the important conclusions of this report as well as identify those research and development topics which ought to be pursued in order to better quantify the environmental impact of UCG. The subsequent discussion is divided into subsections corresponding to the major topics of this report.

UTILIZATION ALTERNATIVES

The major alternatives for use of UCG include power production using low Btu gas and manufacture of chemical products from medium Btu gas, either at the UCG site or some distance away. There is great interest in UCG of Texas lignite, illustrated by field tests at four locations. The technology for air or oxygen injection is reasonably mature, with a number of successful tests having been performed in the U.S.A. and U.S.S.R. Oxygen injection and subsequent processing of the medium Btu gas to produce methanol or gasoline is one promising technological alternative for use in Texas.

RESOURCES OF TEXAS LIGNITE

An extensive subsurface study of lignite in Texas has led to the development of a fairly complete regional exploration model for lignite. New resource maps for the Wilcox and Jackson Groups in South Texas have been completed. This model has allowed the estimation of deep basin lignite resources which might be recoverable via underground gasification. The minimum seam thickness for economic or technical feasibility has been selected as five feet (1.5m), and the maximum seam depth is considered to be 2000 feet (600 m); approximately 35 billion short tons of lignite, found in five regions, meet these criteria. Resource blocks have also been evaluated in terms of their hydrology and baseline water quality, although the data are limited. Overall geological criteria for selecting gasifier sites have been developed.

The essential elements of an ideal site are:

(1) Large reserves in a multiseam deposit.
(2) Host ground dominated by fine-grained low permeability sediments (i.e., low water productivity).
(3) Lignite seams greater than 5 feet (1.5 m) thick
(4) Seams roofed and floored by thick mud.
(5) Aquifers oriented perpendicular to regional groundwater flow

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direction.

(6) Formation water greater than 10,000 ppm TDS.

(7) Proximity to a recharge area.

Available water quality data for lignite-bearing regions have been accumulated, but the data are sparse and no general trends were noted.

Since in situ gasification will be carried out in the fresh-water column, there is a potential threat of groundwater pollution. A necessary first step to large-scale field testing and eventual pilot plants is the selection of gasification sites that minimize the possibility of pollution. Depending on regulatory philosophy, active recharge areas may be preferred, where it is postulated that pollutants will be carried deep into the subsurface, providing maximum opportunity for natural dilution and attenuation.

Regional hydrochemical mapping (base of fresh water and water quality) and head mapping (potentiometric surface) in the Wilcox and Jackson Groups is proposed to help unravel regional hydrology. Water resistivity can be used to evaluate water quality and is obtained through resistivity or spontaneous potential measurements on electric logs. Head data are available from the Texas Water Resources Data Bank, county reports of the Texas Department of Water Resources, and municipal well field records. From good potentiometric surface mapping flow direction can be predicted. Without information on flow direction monitor wells cannot be properly placed or hydraulic barriers established. Mapped patterns should be compared with lithofacies mapping to broadly characterize the relationship betweeh hydrology and geology.

ENGINEERING AND GEOLOGICAL FACTORS IN UCG

The technical factors which are conducive to application of UCG for Texas lignites have been identified, including coal properties, seam thickness, water influx, and roof collapse. Water influx appears to be a crucial factor in Texas both in linking and gasification and is expected to be more of problem in the Wilcox Group than the Jackson Group. Field test data from Texas sites, all in the Wilcox Group have shown very high water influxes; mathematical model calculations for gas composition indicate that the thermal efficiency of the process suffers greatly for large water influx rates. This suggests that dewatering of a site may have a beneficial effect on heating value and thermal efficiency. This hypothesis, however, has not been field tested to fully quantify its potential. Calculations on design and operation of dewatering wells could provide some insight as to the economic trade-offs of such wells. The role of production pressure in UCG to reduce water influx is also poorly understood. A priori estimates of water influx for a given site are desirable but are difficult to calculate with present knowledge.

The relationships among roof collapse, subsidence, and sweep efficiency need to be better quantified before the environmental impact of high sweep efficiency can be assessed. Better correlations for pillar design for weak overburden are required; these ought to be both empirically and theoretically based.

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ENVIRONMENTAL IMPACTS FROM UCG

Water Pollution

Available data on inorganic and organic water pollutants have been accumulated and analyzed. The organic compounds include light hydrocarbons, phenols, oils, and tars. Heavier organics include some polynuclear aromatic hydrocarbons (PAHs) and heterocyclic compounds. Other gaseous components that condense or are absorbed in surrounding groundwater are ammonia, carbon dioxide, hydrogen sulfide, and methane.

After gasification is completed, an ash residue remains in the burn cavity which yields soluble inorganic components to reinvading groundwaters. The soluble ash components can greatly increase the total dissolved solids content of the groundwater. These soluble materials include a wide array of ionic species, mainly calcium, sodium, sulfate, and bicarbonate. These components yield increases in non-specific parameters such as conductivity and total dissolved solids. The exact quantities of these materials are a function of initial coal composition, combustion temperature, water temperature, and groundwater composition. There are, however, many other inorganic materials leached into the groundwater which are of interest even though they are present in lesser quantities. These include aluminum, arsenic, barium, boron, iron, zinc, cyanide, selenium, and hydroxide. Again the exact composition depends on the variables cited above.

Field data have indicated that the pollutants tend to decrease both with time and distance from the burn cavities. There are natural means by which the groundwater concentrations can be reduced. Most interpretations of field data attribute the improved water quality to adsorption and ion exchange properties of surrounding strata, precipitation reactions, dilution and dispersion by groundwater flow, and biological conversion reactions. It should be noted that only the last process, biological conversion, is ultimately useful in the final destruction or conversion of harmful contaminants to nonharmful products.

The conceptual model of pollutant generation and transport proposed in the literature appears valid. Materials having little affinity for solid surfaces, such as many of the TDS components, will not be retained by surrounding strata and will travel at the rate of groundwater flow with little diminution of peak concentrations. Those materials with medium to large affinity for solid surfaces will travel much more slowly and have significant decreases in peak concentrations as time progresses. However, more study on the fate of pollutants is needed because the mechanisms of ion exchange and adsorption (upon which the models are based) do not eliminate the pollutants from the groundwater systems. Study of biological conversion processes is also needed to establish the ultimate fate of the slow-moving contaminants.

Of particular concern is the deposition of tars and oils in the surrounding strata. Some of the materials comprising the tars and oils are toxic chemicals. It appears that the solubility of these components are very low and they have high adsorption affinity for surrounding solid strata. Thus, aqueous concentrations of these components should be low in the region of the

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tar deposits, and their high affinity for solid surfaces should prevent rapid migration in the water phase. However, considering solubility and adsorption only, it should take a very long time before the source of polution is dispersed, but little quantitative information is available. Also unknown is the effect of oxygen vs. air injection on the organic pollutants.

It is especially important to be able to predict the effect of coal and ash composition on organic and inorganic releases to groundwater. Very little laboratory or field data exist which could be used to develop even preliminary correlations.

Air Pollution

The impact from air emissions from UCG has much broader geographical ramifications than the water quality problem, which is more site-specific in nature. Air emissions from a UCG facility plus conversion plant are expected to be lower than those resulting from conventional coal burning steam-electric plant. The gas cleanup operations for UCG should be the same as those needed for surface gasification plants. For a given region, the lower emissions would mean that the available PSD increments in pollutant concentrations in ambient air are consumed to a lesser extent by each new source or major modification. This could promote a greater industrial growth in the region while minimizing adverse environmental effects on air quality. A qualitative analysis of existing emission sources in those regions where UCG might be used reveals few sources which affect air quality. However, a more detailed study involving meteorological considerations should be performed.

Subsidence

The prediction of roof collapse and subsequent surface subsidence is not possible given the state of knowledge for large scale rock mechanics. The surface subsidence is site-specific, and available field data do not allow any specific conclusions regarding predicted subsidence at Texas sites for a commercial operation. Only one U.S. field test (Hoe Creek III) has experienced measurable subsidence. The relatively thin seams of Texas lignite do appear to be advantageous for minimizing surface movement.

SUBSURFACE POLLUTANT TRANSPORT AND MIGRATION

Dispersion of these potential groundwater pollutants has been analyzed and found not to be very significant, due to low groundwater velocities (typically one meter/year or less). Disturbance of aquifer flow patterns and local hydrology may, however, result from roof collapse after gasification is completed. An important consideration in dispersion analysis is the ability of the subsurface strata to adsorb potential contaminants, thus gradually improving water quality after gasification.

The general mathematical models used for prediction and simulation of flow and transport are deemed to be adequate. The science and art of numerical modeling is highly developed, and there are few physical problems which defy analysis. The limitation of numerical models lies in the difficulty in finding the appropriate parameter values to use in the models. This "inverse

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problem" of finding the parameter values is being intensively researched at present and remains a pressing problem for the future. No completely satisfactory procedures are available at present.

The trade-off between the convective and dispersive terms in a mathematical model with different scales of heterogeneities remains a fundamental problem in the analysis of field transport problems. Use of very advanced chemical models will offer limited rewards in field simulations if the hydraulics is poorly represented. An approach to this problem which shows some promise but required further investigation is conditional simulation, where parameters can very according to a stochastic process.

Fractures within the porous media present a number of problems for modeling. There is no generally accepted model of the hydraulics of flow in fractured media. Also development of fractures in the overburden presents an avenue for increased cross-formation flow between neighboring water bearing units. This problem of the interaction of overburden fractures with the regional groundwater flow should be investigated in the future.

Since it is evident that contamination from the gasification site will not be immediate, one must consider changes in water use patterns in the future and how contamination might influence these patterns. Of special interest is increase in hydraulic gradients and the corresponding increase in the rate of contaminant transport.

RESTORATION AND WATER POLLUTION CONTROL OF UCG SITES

Monitoring of water quality during and after field tests have shown that water quality can return to baseline levels as early as one year after the test is completed. This poses some interesting questions regarding use of control technologies as well as restoration strategies. Regulations dealing with this issue are not finalized, and the site-specific characteristics of UCG, both operationally and environmentally, further complicate the issue.

At this time it is not possible to explain completely the improvement in water quality with time or to predict the long term fate of pollutants released to groundwater. Clearly, the mechanisms are complex with many potential physical, chemical, and biological processes that could be important. With the exception of some study of the adsorptive properties of organic compounds on surrounding strate, the important mechanisms affecting long term fate of pollutants are not known. There has been no long term field test from which to obtain real time environmental data, and none of the U.S. tests have been on a commercial scale.

Although local contamination of groundwater can occur, in some cases restoration may not be necessary. It can be argued that regulations on restoration should be flexible (decided on an individual case basis) rather than universally requiring all groundwater to be restored. The following questions should be addressed for a given site:

(1) Is the water quality of an aquifer high?
(2) Is the aquifer productive?
(3) Is the aquifer now or potentially a usable source of water?

An aquifer might be declared exempt from restoration (or minimal restoration

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efforts would be required) if it failed one or more of the above conditions. Restoration bases that have been used in the past in Texas are:

(1) Restoration shall be equal to or better than drinking water standards.
(2) Restoration shall be to baseline water quality or better.

Techniques that could be used for subsurface restoration include:

(1) Treatment of pumped water plus reinjection to the aquifer.
(2) Reliance on natural restoration processes to cleanse the in situ water.
(3) Enhancement of the in situ natural restoration processes.

It should be pointed out that techniques (2) and (3) are not based on established knowledge or practice and require development. In addition, the efficiency of method (1) is not known at this time either, although it is commonly used to restore in situ uranium leaching sites.

The treatment and/or disposal of the contaminated water from UCG has not been studied as yet. However, treatment of similar types of waters from in-situ shale oil retorting and above ground coal gasification processes has been studied. However, no full-scale treatment scheme exists and wastewaters specific to in situ coal gasification have not been analyzed in treatability studies.

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